Instream flow studies on Crandall Creek, tributary to the Clarks Fork River

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ABSTRACT

Crandall Creek has been identified as crucial habitat for a conservation population of Yellowstone cutthroat trout (YCT; *Oncorhynchus clarki bouvieri*), an important game fish and species of greatest conservation need in Wyoming. Though YCT were historically widespread throughout the Clarks Fork drainage, only a few conservation populations remain. To help ensure the persistence of this population, the WGFD has selected the stream for consideration of an instream flow water right filing. Securing an instream flow water right in Crandall Creek will help ensure that YCT remain in the creek by protecting existing base flow conditions against potential future consumptive water demands.

An instream flow investigation was conducted on Crandall Creek in 2014 and the resulting flow recommendations are reported here. One stream segment was selected for the study, which was chosen considering land ownership, hydrology, and stream channel characteristics to maintain or improve the important YCT population. Several modeling techniques were employed within the study segment to evaluate YCT habitat availability and develop flow recommendations including two-dimensional habitat modeling using River 2D, the Habitat Retention Method, and Habitat Quality Index (HQI) modeling. River 2D was used to calculate habitat availability for all life stages of YCT over a range of flow conditions. The Habitat Retention Method was used to examine riffle hydraulic characteristics needed to maintain fish passage (longitudinal connectivity) between habitat types and provide sufficient depth, velocity, and wetted area to ensure survival of fish prey items (benthic invertebrates). The Habitat Quality Index (HQI) model was used to assess the relationship between stream flow and juvenile and adult trout habitat quality in the summer. During winter months, October through April, natural flows, represented by the 20% monthly exceedance values, were recommended to maintain all life stages. Finally, a dynamic hydrograph model was used to quantify flow needs for maintenance of channel geomorphology.

Results of the instream flow investigation on Crandall Creek indicate that flows ranging from 27 cubic feet per second (cfs) during the winter to 66 cfs during spring are needed to maintain YCT habitat in the segment. If this instream flow application advances to permit status, approximately 1.7 miles of stream habitat in Crandall Creek will be directly protected allowing for YCT spawning, passage, and year round survival.

INTRODUCTION

Rivers and streams, and their associated fisheries, are important to the residents of Wyoming, as evidenced by the passage of the Wyoming Statute 41-3-1001-1014 which recognizes that protection of stream flows for fisheries with instream flow water rights is a beneficial use of water. The Wyoming Game and Fish Department (WGFD) works to protect fisheries throughout the state using various tools and strategies, including proposing instream flow water rights where it is appropriate and beneficial. Detailed background information on instream flows in Wyoming is presented in Appendix A. Guidance for selecting streams to evaluate for instream flow water right consideration is provided by WGFD's Water Management Plan (Robertson and Annear 2011).

One of the highest current priorities for new instream flow projects are streams containing Yellowstone cutthroat trout (YCT; *Oncorhynchus clarki bouvieri*). Among the streams that contain populations of YCT, several have modified habitat conditions that have restricted the YCT populations to isolated reaches relative to the watershed-wide distributions that the species once inhabited. These remaining isolated reaches are important for conservation efforts, including maintaining sufficient stream flow to ensure long-term persistence to the extent allowed within the current interpretation of the instream flow statute.

Crandall Creek was identified as a high priority area for securing an instream flow water right for the preservation and maintenance of YCT. Crandall Creek occurs within a "crucial" habitat area as identified in the WGFD Strategic Habitat Plan (SHP) (WGFD 2009) and a "conservation area" in the WGFD State Wildlife Action Plan (2010). According to the SHP, "crucial habitats have the highest biological values, which should be protected and managed to maintain healthy, viable populations of terrestrial and aquatic wildlife. These include habitats that need to be maintained as well as habitats that have deteriorated and should be enhanced or restored." In addition, Crandall Creek contains a conservation population of YCT as defined by the multi-state recovery team, which indicates that it is genetically pure and has the potential for reproductive exchange with other YCT populations in the stream network (May et al. 2007).

This report details the results of the Crandall Creek instream flow study conducted in July through September 2014. Flow recommendations are based upon consideration of the five primary riverine components that influence the characteristics of a stream or river: hydrology, biology, geomorphology, water quality and connectivity (Annear et al. 2004). Maintaining sufficient water of good quality is essential for sustaining fish productivity in streams and rivers. When water resources are developed in Wyoming for out-of-stream, consumptive uses, there are corresponding changes in riverine components that alter the ability of a stream to support fisheries habitat. The five riverine components were evaluated using various models and data sources to generate the recommendations for how much flow should remain in Crandall Creek (when naturally available) to provide sufficient habitat during important time periods in the life stages of YCT.

The objective of this study was to quantify instream flow levels needed to maintain YCT habitat in Crandall Creek during critical seasonal periods. In addition, a channel maintenance flow regime was modeled that will maintain long-term trout habitat and related physical and biological processes (Appendix B). The information can be used as supporting material for a supplemental instream flow water right application. The audience for this report includes the Wyoming State Engineer and staff, the Wyoming Water Development Office, aquatic habitat and fishery managers, and non-governmental organizations and individuals interested in instream flow water rights.

STUDY AREA

Crandall Creek, located in Park County Wyoming, is a tributary of the Clarks Fork River (Figure 1). The stream is located within the Cody region of the WGFD. The watershed (HUC10 1007000602) encompasses approximately 35.5 square miles. Land ownership in the watershed includes 99% Forest Service land and 1% private ownership. The private land is located at the downstream end of Crandall Creek, below the proposed instream flow segment.

The highest point in the Crandall Creek watershed is approximately 11,580 ft and the lowest point, at the downstream end of the study segment, is approximately 6,490 ft. Annual precipitation averaged 15.5 inches in the area of the stream over the period 1895–2012 according to data retrieved from the Wyoming Water Resources Data System (WRDS 2015).

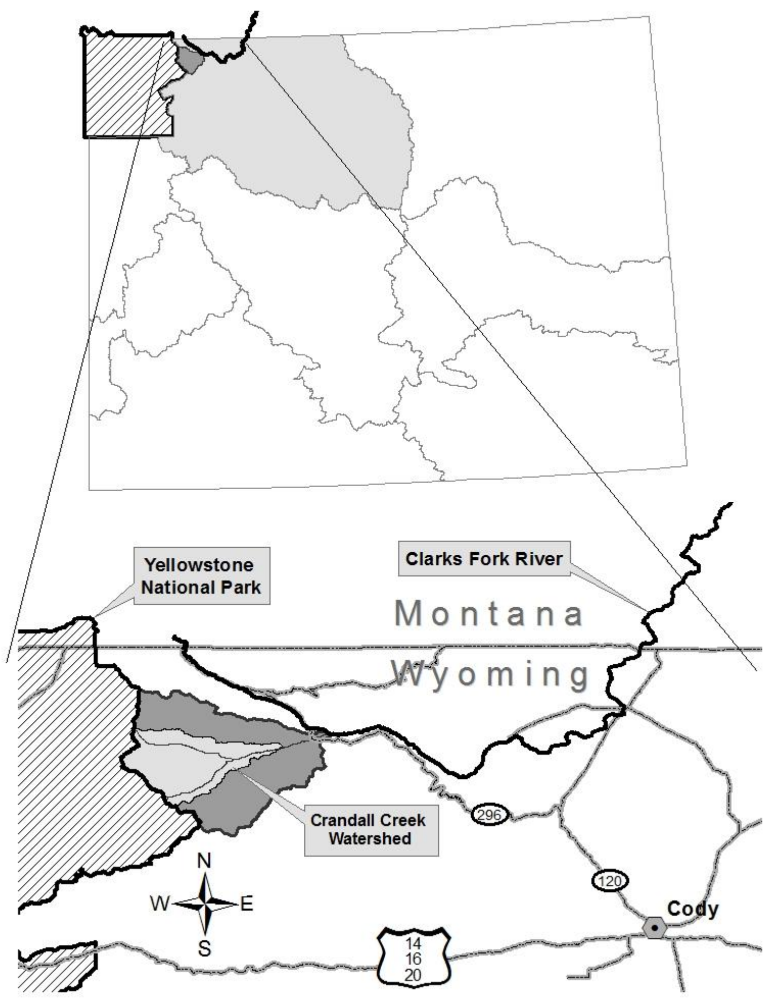

FIGURE 1. Location of Crandall Creek, WY (HUC 1007000602).

The fish community in Crandall Creek includes rainbow trout (*Oncorhynchus mykiss*), Snake River cutthroat trout (*Oncorhynchus clarkii behnkei*), YCT, and hybrids of RBT and cutthroat trout. The current management objective is to maintain a wild population of YCT. Evaluation of flow conditions that are necessary to maintain or improve this fishery was conducted using the habitat and hydrological modeling efforts described below.

METHODS

This report details the results of the Crandall Creek instream flow study conducted in July through September 2014.

Instream Flow Segment and Study Site Collection

One stream segment is proposed for an instream flow water right filing on Crandall Creek (Table 1; Figure 2). The boundaries for the segment were identified after considering land ownership, hydrology, and stream channel characteristics. The downstream end of the segment is at the confluence with North Fork Crandall Creek and the upstream boundary is at the confluence with Hoodoo Creek approximately 1.7 miles upstream. The YCT population extends further upstream, but that portion of the stream is in the North Absaroka Wilderness. The instream flow segment selected on Crandall Creek is located entirely on public land.

TABLE 1. Location, length, and elevation at the downstream end of the proposed instream flow segment on Crandall Creek.

Segment	Description	Length (mi)	Elevation (ft)
Crandall Creek	Begins at confluence with North Fork Crandall Creek and extends upstream to confluence with Hoodoo Creek.	1.74	6,490

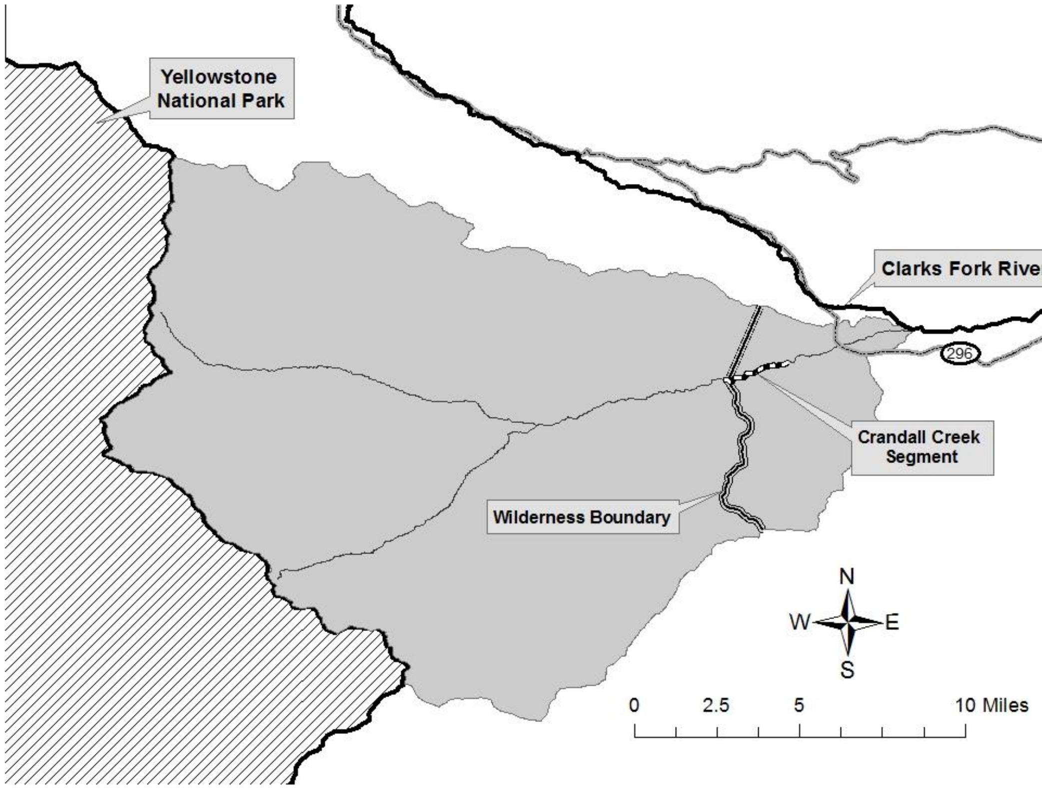

FIGURE 2. Data were collected to evaluate fish habitat at one potential instream flow segment on Crandall Creek.

Within the instream flow segment, one study site of approximately 750 ft of stream was selected to represent habitat conditions in the segment. Because the bankfull width in this reach was approximately 73 ft, the study site length was equal to approximately 10 times the channel width. This is on the low end of reach length recommended by Bovee (1982; 10-14 times the channel width), but extending the reach further upstream or down would not have improved modeling efforts using the River 2D model because in both directions there was a long stretch of uniform run habitat.

The study site was one continuous reach of stream modeled using the two-dimensional River 2D model and also included 3 transects (Figure 3) downstream. The three transects were all riffles, which are used in habitat retention modeling (see below for details). The complexity of this site is representative of the range of habitat conditions available in the instream flow segment. The complexity of this study site is representative of the range of habitat conditions available throughout the instream flow segment. All data collection was conducted in this study site and extrapolated to the entire proposed instream flow segment.

FIGURE 3. One of four transects at the Crandall Creek study site. The discharge at the time of the photo was 177 cfs.

Hydrology

Development of flow recommendations for an instream flow study segment requires an understanding of hydrology within the study segment. There are no stream gage data available within the segment so flow conditions were estimated from a regional reference gage (see Appendix C for details). The USGS gage on Sunlight Creek (06206500) was selected as the reference gage for these analyses (Figures 4, 5). This gage was active from 1945 to 1971, a 26 year period of record, and was located within the Clarks Fork River drainage near the ungaged study site. Based on its proximity, it is suspected that precipitation and runoff patterns are similar between the reference gage and the study site.

The estimates of the hydrologic characteristics in the instream flow segment were used in several ways. Average daily flow estimates were used in applying the Habitat Quality Index and Habitat Retention Models (described below). The 1.5-year return interval on the flood frequency series was used to estimate bankfull flow (Rosgen 1996) for use in the Habitat Retention Model and for developing channel maintenance flow recommendations (Appendix B). Channel maintenance calculations required the 25-year peak flow estimate from the flood frequency analysis. In addition, the monthly flow duration curve was used in developing winter flow recommendations. Flow duration curves indicate the percent of time that a given flow is equaled or exceeded. The 20% exceedance flow was identified for this analysis, which refers to the flow level that would be present approximately one year out of every five consecutive years.

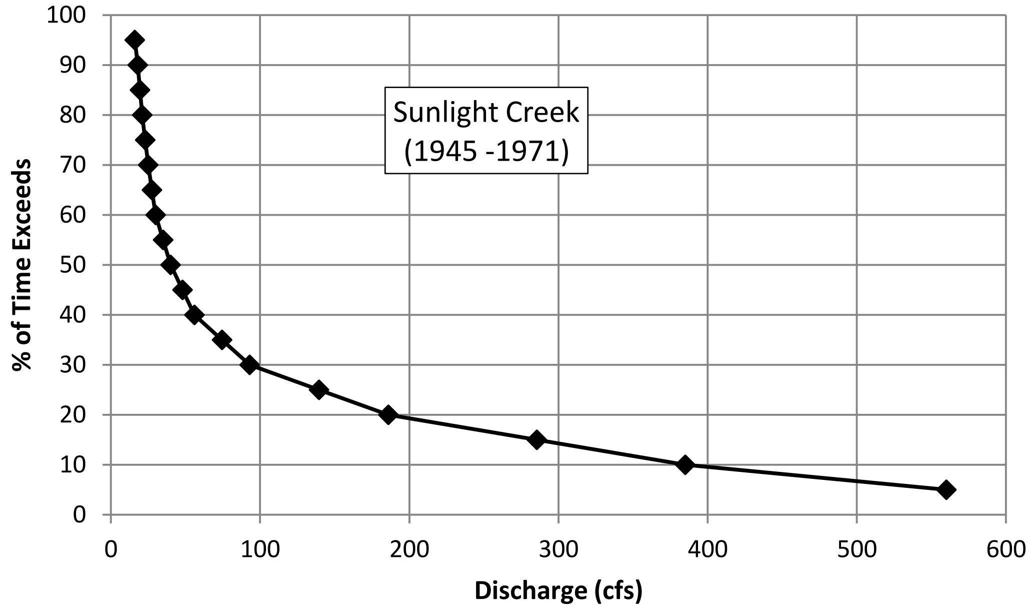

FIGURE 4. Flow exceedance curve for the Sunlight Creek USGS stream gage station (06206500) over the period of record (1945-1971).

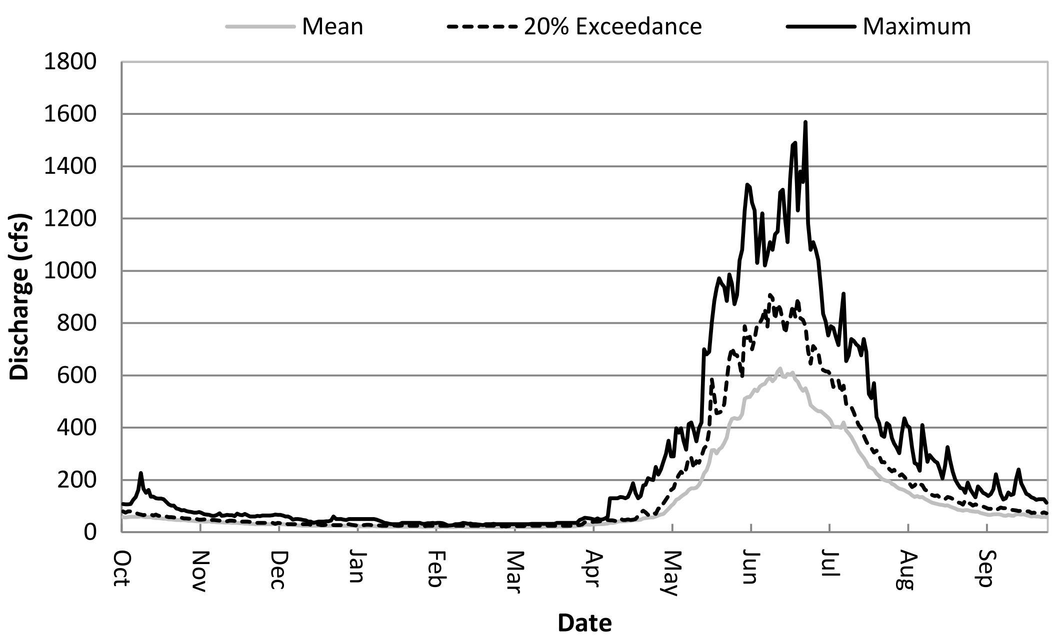

FIGURE 5. Hydrograph showing the mean, 20 percent exceedance, and maximum daily discharge for each day over the period of record (1945-1971) at the Sunlight Creek USGS stream gage station (06206500).

Biology – Fish Habitat Modeling

Habitat preferences of target fish species, including each of their life stages, are important in instream flow studies since flow recommendations are based on maintaining sufficient habitat for target species to survive, grow, and reproduce. Species-specific habitat preferences are used to develop habitat suitability curves that are in turn used in habitat models.

Availability of fish habitat in the study site was evaluated using several different habitat models. "Habitat" in this report refers to the combination of physical conditions (depth, velocity, substrate, and cover) for a given area. These physical conditions vary with discharge. It is important to note that these variables do not represent a complete account of all variables that comprise trout habitat. Habitat for trout also includes environmental elements such as water temperature, dissolved oxygen, and other variables. These other variables are important, but are not included in models used for these analyses because they do not fluctuate with changes in the quantity of flow as predictably as the physical habitat parameters. Interpretation of model results based on these physical habitat parameters assumes that this subset of trout habitat is important and provides a reasonable indication of habitat availability at each flow and an indirect expression of the ability of trout to persist on at least a short-term basis at those flow levels.

Dey and Annear (2006) found that adult YCT in Trout Creek (tributary of the North Fork Shoshone River) were most commonly found in areas with depths of 1.15–1.60 ft and average column velocities of 0.36–1.91 ft/s. For juvenile YCT, these ranges were slightly different with depths of 1.0–1.5 ft and average column velocities of 0.38–1.65 ft/s (Dey and Annear 2006). Growth rate of adult and juvenile YCT is greatest during the relatively short summer and early fall periods. Adequate flow for these life stages is also critical during winter to allow over-winter survival.

In addition to adults and juveniles, availability of suitable spawning habitat for YCT was evaluated over a range of flows. YCT spawn between March and July throughout their range, depending on local hydrology and water temperatures (believed to be triggered around 41°F; Kiefling 1978, Varley and Gresswell 1988, De Rito 2005). The stream gradient observed in spawning areas is usually less than 3% (Varley and Gresswell 1988), but non-migratory fluvial populations have been documented in streams with a mean gradient of 6% (Meyer et al. 2003). Spawning activity for YCT in Wyoming has been observed during May and June in watersheds within the Bighorn River Basin in north central Wyoming (Greybull River, Shoshone River and their tributaries; Kent 1984, Dey and Annear 2002, Dey and Annear 2006). Elevation has an influence on the timing of spawning in YCT with stream segments located at higher elevations more likely to remain colder and cause delayed spawning and slower egg incubation rates. Dey and Annear (2003) found that spawning in the Greybull watershed occurred into July in streams above approximately 8,000 ft in elevation and extended recommendations for spawning flows through July 15 in such high elevation sites. The instream flow segment on Crandall Creek occurs at about 6,500 ft in elevation. It is possible that spawning may extend into July in the upper portions of the watershed (above the segment), but most activity in the segment likely occurs in June. Dey and Annear (2006) observed too few spawning YCT (n=4) to develop habitat suitability curves for spawning YCT in Wyoming. Spawning YCT habitat suitability data from a Snake River tributary in Idaho are presented in Thurow and King (1994); these researchers found that velocity preference was highest from 1.12 to 1.72 ft/sec and depth preference highest from 0.52 to 0.82 ft. Information from that study was used to indicate habitat selectivity of YCT in Crandall Creek.

River2D Model

The River2D model (Steffler and Blackburn 2002) was used to generate depth and velocity predictions throughout the study reach and to estimate how much habitat is available for YCT at different flow levels. The model provides a detailed characterization of habitat availability throughout the study site and results of the model were evaluated to determine how much stream flow is needed to maintain sufficient habitat for these life stages during critical time periods.

Inputs for the model are a detailed stream bed elevation map, a map of substrates, and a stage-discharge relationship (developed at the downstream boundary) which allow the model to simulate water moving through the site at a given discharge and generate estimates of depth and velocity at any location. We collected all bed elevation points (northing, easting, and elevation) for the River2D model site with a TopCon model 211D total station to create the bed elevation map. Substrate was mapped throughout the site using the categories vegetation, mud, silt, sand, gravel, cobble, boulder, and bedrock. The percentages of dominant and subdominant classes were assigned to each mapped area. The substrate map does not vary with flow, but is used to evaluate habitat preferences of the target species in combination with depth and velocity conditions. The stage-discharge relationship was developed with three discharge measurements during the study, 176.9 cfs, 79.6 cfs, and 65.7 cfs; stage was measured at a point near the downstream end of the study reach.

Additional field data included water surface elevation collected at regularly spaced intervals near both banks throughout the study reach at the three discharge levels described above. These data were compared to model runs at these same discharge values to calibrate the model. Velocity was measured at 20 randomly-selected points across one transect (14 evenly-spaced points across the channel) at 65.7 cfs and the velocity data were compared to velocity estimates at these same locations from the model at the same discharge.

The model was initially set up using the conditions found at the highest measured discharge, 176.9 cfs, and calibrated by adjusting model inputs to improve predictions of water surface elevation throughout the study site. The primary input variable that was adjusted during calibration was substrate roughness. To further refine the model results, groundwater transmissivity was also adjusted (see River2D user manual at http://www.river2d.ualberta.ca/Downloads/documentation/River2D.pdf). Changes were made to substrate roughness values and groundwater transmissivity as needed to achieve the best possible model fit with the available water surface elevation data. Once model predictions of water surface elevation and velocity measurements matched field data as closely as possible, the model was then run using the same model inputs at the middle discharge (79.6 cfs) and further modified until it worked well at both discharges. The process was repeated at the lowest observed discharge (65.7 cfs); the velocity data collected at that discharge were evaluated as well to help determine model fit.

Simulations were conducted using the final calibrated model over the flow range of 5 cfs to 200 cfs. The model was used to simulate depth and velocity conditions throughout the study reach at each of these flows and was used in combination with the substrate map to estimate the total area in the study site that provides suitable habitat conditions (weighted usable area; WUA) for each YCT life stage at each discharge. Results were displayed by graphing WUA for a given life stage versus a range of simulated discharges (Bovee et al. 1998). The values were normalized to a percent of the maximum WUA value as recommended by Payne (2003).

Habitat Retention Model

The Habitat Retention Model (Nehring 1979, Annear and Conder 1984) was used to evaluate hydraulic characteristics that affect the survival and movement of all trout life stages over a range of discharges in the Crandall Creek instream flow segment. The model was used to identify the lowest flow that maintains specified hydraulic criteria in riffles (Table 2). These criteria represent conditions needed to maintain fish passage (longitudinal connectivity) among habitat types and ensure sufficient depths, velocities, and wetted areas for the survival of benthic invertebrates, many of which serve as fish prey (Nehring 1979). Flow recommendations derived from the Habitat Retention Method address portions of the connectivity and biology riverine components. The flow identified by the Habitat Retention Method is important year round, except when greater flows are necessary to meet other behavioral or physiological requirements of the target fish species.

Simulation tools and calibration techniques used for hydraulic simulation in PHABSIM are also used with the Habitat Retention Method. The AVPERM model within the PHABSIM methodology was used to simulate cross section depth, wetted perimeter and velocity for a range of flows. The flow that maintains two out of three criteria for all modeled transects is then identified as the threshold to maintain sufficient flow to meet the needs of the fishery. Because of the critical importance of depth for maintaining fish passage, the 0.2 ft threshold was required to be one of the criteria met for each transect (Table 2). Crandall Creek is wider than 20 feet (mean bankfull width from the three transects), so the mean depth criterion was 0.01 times the mean bankfull width.

TABLE 2. Hydraulic criteria for determining maintenance flow with the Habitat Retention Method (Annear and Conder 1984).

Category	Criteria
Mean Depth (ft)	0.20[a]
Mean Velocity (ft/s)	1.00
Wetted Perimeter[b] (%)	50

a – when transect bankfull width >20 ft, then 0.01 * mean bankfull width
b – Percent of bankfull wetted perimeter, calculated for each transect

Habitat Quality Index Model

The Habitat Quality Index (HQI; Binns and Eiserman 1979, Binns 1982) was used to determine production potential of adult and juvenile YCT in the study site during summer (July through September) flow conditions. Most trout production (growth) in Wyoming streams occurs during summer, following peak runoff, when longer days and warmer water temperatures facilitate growth. Developed by the WGFD, the HQI model uses nine biological, chemical, and physical trout habitat attributes to estimate relative habitat suitability in a stream reach and can be used to predict trout abundance.

For this study, the HQI was used to estimate the number of YCT habitat units in the study reach, each of which is expected to support about 1 pound of trout. Data were collected for HQI calculations at 177 cfs, 80 cfs, and 66 cfs between July 1 and September 30 and attribute ratings were interpolated between these measurements to characterize the relationship between discharge and trout habitat conditions at discharges other than those measured (Conder and Annear 1987).

Article 10, Section d of the Wyoming Instream Flow statute states that waters used for providing instream flow water rights "shall be the minimum flow necessary to maintain or improve existing fisheries." To maintain a viable trout fishery, it is critical to maintain normal late summer flows, which can be represented by the September 20% monthly exceedance flow. The HQI results were used to identify the number of habitat units that occur at this flow and the lowest flow that maintains that quantity of habitat.

Natural Winter Flow

Low water temperature, which reduces metabolic rates, reduced living space associated with naturally lower flow conditions during this season, and the lack of food are all factors that make the winter a stressful time period for fish in Wyoming Rocky Mountain headwater streams (Locke and Paul 2011). Even relatively minor flow reduction at this time of year can change the frequency and severity of ice formation, force trout to move more frequently, affect distribution and retention of trout, and reduce the holding capacity of the few large pools often harboring a substantial proportion of the total trout population (Lindstrom and Hubert 2004).

The habitat modeling approaches described above are not well suited to determine flow requirements during ice-prone times of year. These methods were all developed for and apply primarily to open-water periods. Ice development during winter months can change the hydraulic properties of water flowing through some stream channels and compromise the utility of models developed for open water conditions. The complexities of variable icing patterns make direct modeling of winter trout habitat over a range of flows difficult if not impossible. For example, frazil and surface ice may form and break up on multiple occasions during the winter over widely ranging spatial and temporal scales. Even cases that can be modeled, for example a stable ice cap over a simple pool, may not yield a result worthy of the considerable time and expense necessary to calibrate an ice model. There are no widely accepted aquatic habitat models for quantifying instream flow needs for fish in under-ice conditions (Annear et al. 2004). As a result, a different approach was used to develop recommendations for winter flows.

To determine the winter flow necessary to maintain the YCT fishery in Crandall Creek, the 20% monthly exceedance value was estimated. Whereas other flow values may be sufficient to support the fishery at other times of the year, the 20% monthly exceedance flow is most appropriate in winter. Hubert et al. (1997) observed that poor gage records often associated with the winter season requires use of a conservative value. Their studies showed that 50% monthly exceedance does not provide an appropriate estimate of naturally occurring winter flow. This approach assures that even in cases where flow availability is underestimated due to poor gage records or other estimation errors, habitat associated with flow that approximates natural winter conditions will be protected.

Geomorphology

Maintaining appropriate stream channel characteristics in a given stream reach is important for preventing loss of fish habitat throughout that stream. Reductions in flow quantity can affect the sediment load balance such that its transport capacity is diminished and excess fine sediments and small gravel aggrade in the channel (Bovee et al. 1998). This usually reduces habitat suitability for fish communities by degrading the quality of riffles, filling pools, and allowing stream bank encroachment. Other physical changes in the stream caused by road building, culvert addition, riparian habitat reduction, and other activities also affect sediment transport dynamics. In streams compromised with streambank instability that have additional sediment inputs from land management practices (extensive grazing and channel alterations) and road construction and maintenance activities in the watershed, reduction in natural flow conditions makes it even more difficult for the stream to move sediment sufficiently to prevent aggradation.

The geomorphology conditions of the proposed instream flow segment were evaluated by visual observation. Observations on channel form characteristics including Rosgen channel type, sinuosity, and riparian habitat conditions were noted. In addition, roads, culverts and other changes to the watershed were identified along with areas of excessive erosion and any imbalance in sediment load conditions. This visual assessment also included observations on the influence of substrate sizes and large woody debris on pool development and habitat conditions for the fish community.

An evaluation of high flows that are important for channel maintenance and necessary to maintain existing fisheries on a long-term basis was not included in the main body of the report since the current interpretation of the instream flow statute does not allow issuance of water rights for such high flow regimes. Recommendations for flows sufficient to allow channel maintenance and to fully maintain fishery habitat in the segment are presented in Appendix B. Should opportunities arise in the future to secure instream flow water rights for long-term maintenance of stream habitat conditions, this information will provide a valuable reference.

Water Quality

Water temperature in late summer and fall has been found to be a limiting factor for many trout populations and this data is critical to consider in development of an instream flow recommendation. The evaluation of water temperature in the proposed instream flow segment included reviewing model results from the USFS Rocky Mountain Research station NorWeST model (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html). That model is based on data collected at various points throughout the Yellowstone River HUC6 watershed (100700), including the Upper Clarks Fork catchment, and estimates water temperature in all streams and tributaries throughout the watershed.

In addition, a Nitrate + Nitrite-N sample was collected and analyzed by the Wyoming Department of Agriculture Analytical Services Laboratory. Finally, the Wyoming Department of Environmental Quality classification was noted and any sampling conducted by that agency or any other entities (using the EPA STORET database) to determine existing water quality conditions and the potential for deterioration with reduced water flow was considered as part of the evaluation.

Connectivity

River system connectivity is manifested along four dimensions: longitudinal, lateral, vertical, and temporal (Ward 1989). Longitudinal connectivity is important for allowing ease of movement of organisms and organic material up and downstream within the watershed. Lateral connectivity is critical to the functioning of stream ecosystems in order to facilitate exchange of nutrients and organic matter between the floodplain and the stream during floods. This process often drives development of aquatic food elements that affects productivity of the fish. The seasonal flooding of unregulated streams creates and maintains diverse species of riparian vegetation (Nilsson et al. 1989), which adds stream channel stability and fosters diverse animal communities both within and adjacent to the stream channel. In addition, the ability to dissipate energy out onto the floodplain is important to reducing damage to the stream channel itself, and downstream infrastructure.

In developing instream flow recommendations for the proposed segment, the presence of barriers to longitudinal connectivity were considered for physical, chemical, and even biological conditions in all four dimensions. The Habitat Retention Method was used to quantify the flow needed to maintain hydrologic connectivity within the stream channel. However, no detailed assessment was conducted to quantify flows needed to maintain lateral connectivity nor was an assessment done to evaluate the relationship between ground water and flow (vertical connectivity). Though the ability of the stream to transport of nutrients, energy and sediments was beyond the technical and legal scope of this study, this process is important in a properly functioning stream environment.

Instream Flow Regime Recommendations

Data from the evaluation of all five riverine components were considered in developing instream flow recommendations for YCT in Crandall Creek. However, Wyoming statute 41-3-1001-1014, which declares that instream flows may be appropriated for maintaining or improving fisheries, has been interpreted by Wyoming state engineers to include only hydrology and fisheries components of streams. This interpretation limits the ability to include the other riverine components (geomorphology, water quality, and connectivity) as a basis for quantifying flow regime needs for maintaining fisheries. Though not specifically included in the flow recommendations, information on these other important riverine components on Crandall Creek is presented in this report, including a detailed discussion of channel maintenance flows in Appendix B. The recommendations resulting from these analyses are expected to maintain short-term habitat for YCT in Crandall Creek, but do not consider changes in natural geomorphic characteristics and habitat forming processes of the stream that are expected to occur over time intervals of decades or longer.

Instream flow recommendations were generated for three seasonal periods that are most critical to the various life stages of YCT in Crandall Creek. The timing and duration of each seasonal period is based on YCT biology and hydrology information from the reference gage (Table 3; Figure 6). Over-winter survival of adult and juvenile YCT is addressed with natural winter flow from October 1 through April 30. The estimated hydrograph indicates that, on average, low base flow conditions in winter occur between November and March during both the highest and lowest flows recorded. However, average flows are still relatively low in October and April and because this is a high elevation stream, it is subject to icing during these periods. In addition water temperatures are low enough that fishes seek refuge and reduce activity similar to the winter period. Spawning and incubation habitat for YCT is quantified using River 2D habitat modeling results for the period May 1 to June 30. Summer habitat for growth and production of adult and juvenile YCT is quantified with Habitat Quality Index results and River 2D modeling results for the period July 1–September 30.

The models used for developing the recommendation for a given season were selected based on their appropriateness for the characteristics and flow needs at the study site. Some models (e.g., Habitat Quality Index) are more suited to certain life stages and time periods so each was used during the season that was most appropriate. In some cases, the ecological characteristics and issues at a study site were unique and models used for developing flow recommendations in other studies were not necessarily appropriate in this situation. When two or more methods were appropriate for developing a flow recommendation, the one that yields the higher flow requirement was chosen.

TABLE 3. Yellowstone cutthroat trout life stages and seasons considered in developing instream flow recommendations. Numbers indicate the method used for each combination of season and life stage, and gray shading indicates the primary data used for flow recommendations in each season.

Life stage and Fishery Function	**Over-Winter Oct 1 – Apr 30**	**Spring May 1 – Jun 30**	**Summer Jul 1 – Sep 30**
Survival of all life stages	1		
Connectivity between habitats	2	2	2
Adult and juvenile habitat availability	3	3	3
Spawning habitat availability		3	
Adult and juvenile growth			4
Habitat maintenance for all life stages*		5	

1=Natural winter flow or Habitat Retention, whichever is greater, 2=Habitat Retention, 3=Physical Habitat Simulation, 4=Habitat Quality Index, 5=Channel Maintenance.
* Channel maintenance flow recommendations are presented in Appendix B.

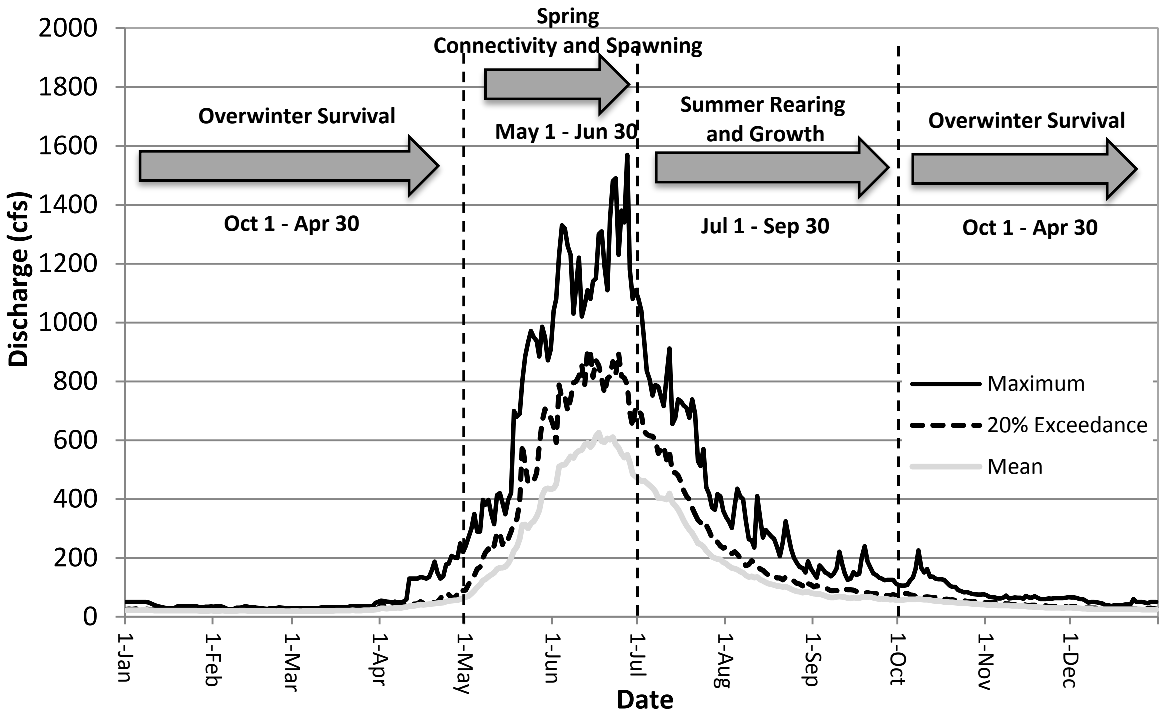

FIGURE 6. Mean, 20 percent exceedance, and maximum daily historical discharge values over the period of record at the reference gage with critical time periods for YCT distinguished. Discharge data are from the USGS stream gage on Sunlight Creek (06206500).

RESULTS

Hydrology

Streamflow in the study area was high in 2014 compared to historic flow levels. On the Lamar River (USGS gage 06188000) to the west, mean annual discharge in 2014 ranked as the ninth highest flow year over a 72 year period of record. The high flows delayed the onset of the field study as runoff occurred later and over a longer time period than during normal or low flow years. Base flows in the fall also may not have been as low as in other years. Nonetheless, all necessary data were collected to complete the study.

Mean annual flow was estimated to be 98 cfs in the Crandall Creek instream flow segment; flood frequency analysis indicates that the 1.5-year peak flow is 775 cfs and the 25 year peak flow is 1852 cfs (Table 4). Monthly flow duration estimates, including 50% and 20% exceedance values, are displayed in Table 5. Discharge data collected during the study are presented in Table 6. In addition, a hydrograph was prepared that shows the mean, 20 percent exceedance, and maximum daily discharge estimate over the period of record in the study site (Figure 7).

TABLE 4. Estimated hydrologic characteristics for the Crandall Creek instream flow segment.

Flow Parameter	**Estimated Flow (cfs)**
Mean Annual	98
1.5-year peak	775
25-year peak	1852

TABLE 5. Estimated hydrologic characteristics for the Crandall Creek instream flow segment.

Month	**50% Exceedance (cfs)**	**20% Exceedance (cfs)**
October	34	45
November	25	31
December	19	23
January	15	18
February	15	16
March	15	18
April	23	36
May	131	253
June	380	595
July	230	361
August	81	115
September	44	62

TABLE 6. Dates of collection and discharge measurements collected in the Crandall Creek instream flow segment in 2014.

Date	**Discharge (cfs)**
7/25/14	177
8/16/14	80
9/26/14	66

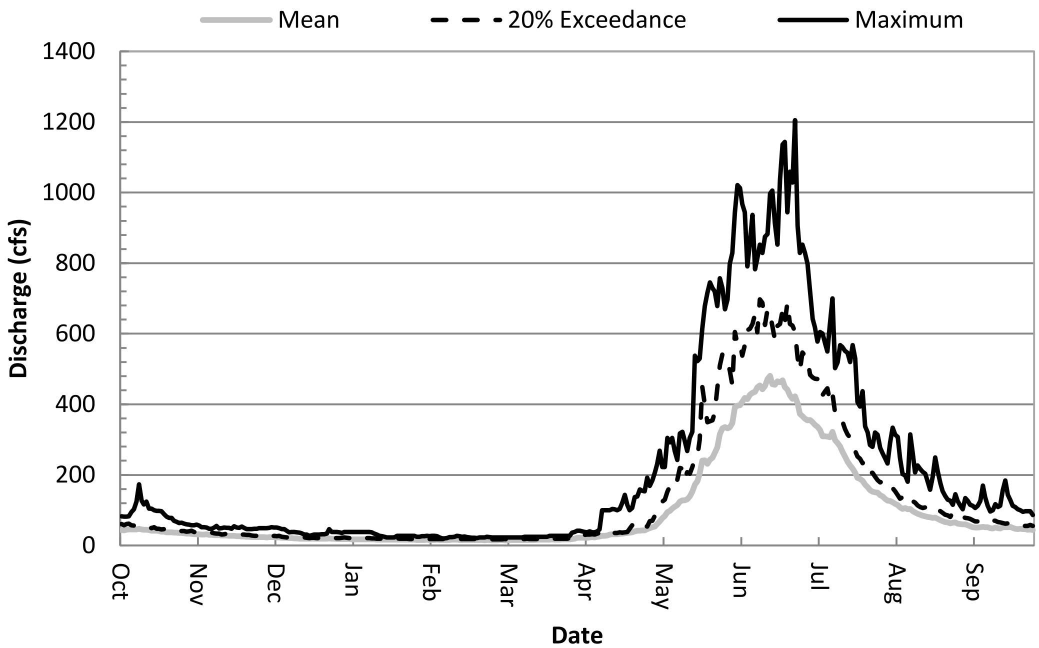

FIGURE 7. Hydrograph showing the mean, 20 percent exceedance, and maximum daily discharge estimates for the for the Crandall Creek study site.

Biology – Fish Habitat Modeling

River2D Model

The River 2D model was used to estimate habitat for adult, juvenile and spawning life stages of YCT. The combination of model input conditions that provided the best fit between simulated and observed water surface elevation and velocity data was using a uniform bed roughness value of 0.50 and groundwater transmissivity value of 0.012. This model yielded simulated water surface elevation values that differed from observed values by an average of 0.02 cm at the 176.9 cfs calibration flow (Figure 8), 1.1 cm at the 79.6 cfs flow (Figure 9), and 1.4 cfs at the 65.7 cfs flow (Figure 10). Velocity points differed by as much as 0.39 m/s, but average differences between simulated and observed values were less than 0.01 m/s for the transect points (Figure 11) and the random points (Figure 12). Considering that velocity at any given point may differ substantially from a nearby point, it is not surprising that several points deviate by quite a bit between the simulated and observed values. These data show that the majority of the velocity points were predicted very closely to the observed value and the pattern of velocity across the transect was similar between the simulated and observed flows. Though there is no universal threshold to indicate a good versus a bad model, these data provide support that the model predicted water elevation and velocity with good reliability.

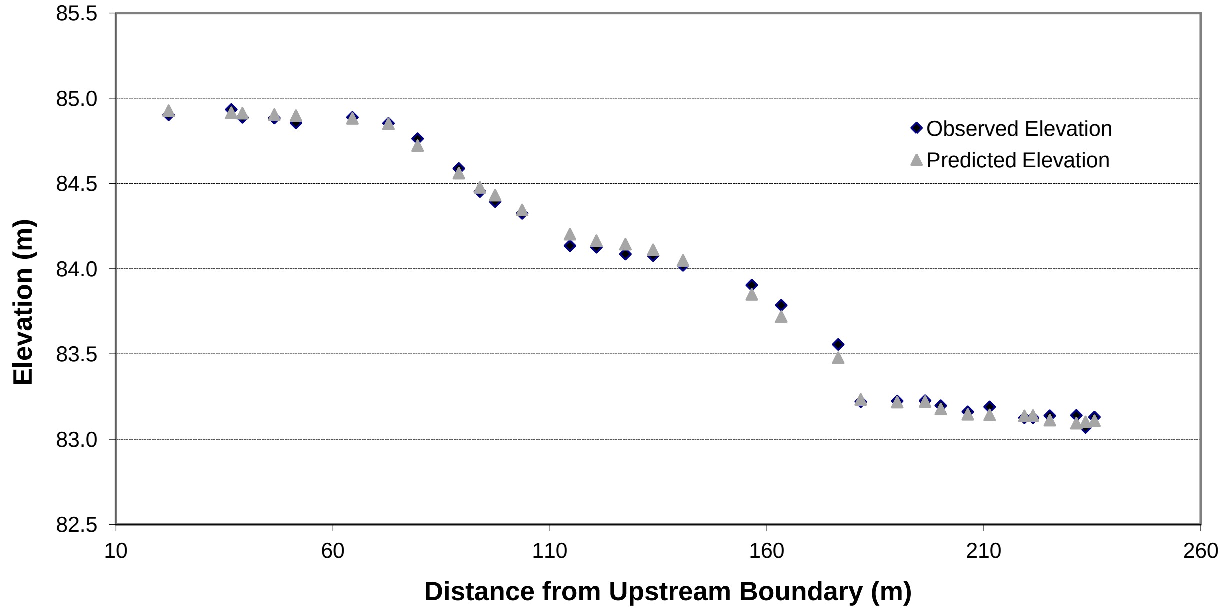

FIGURE 8. Relative abundance of fish captured in the Harmony Ditch entrainment net during 2006 and 2007. Rare species described as "others" include BNT, BBT, LNS, MTS and SMB.

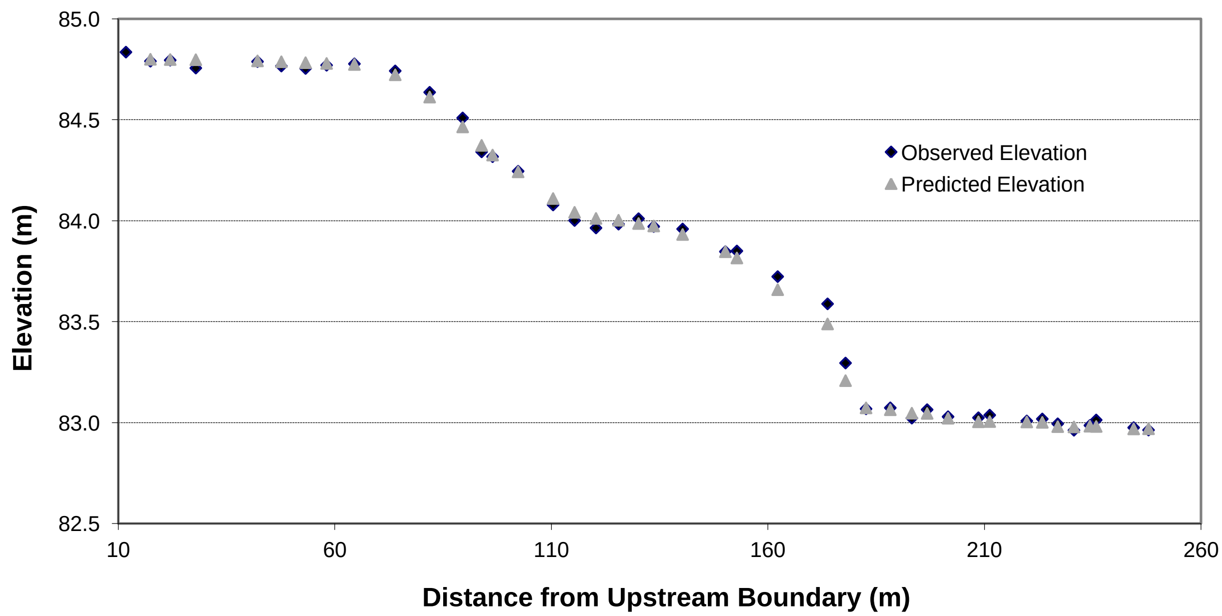

FIGURE 9. Final simulated and observed water surface elevations at 79.6 cfs in the Crandall Creek study site.

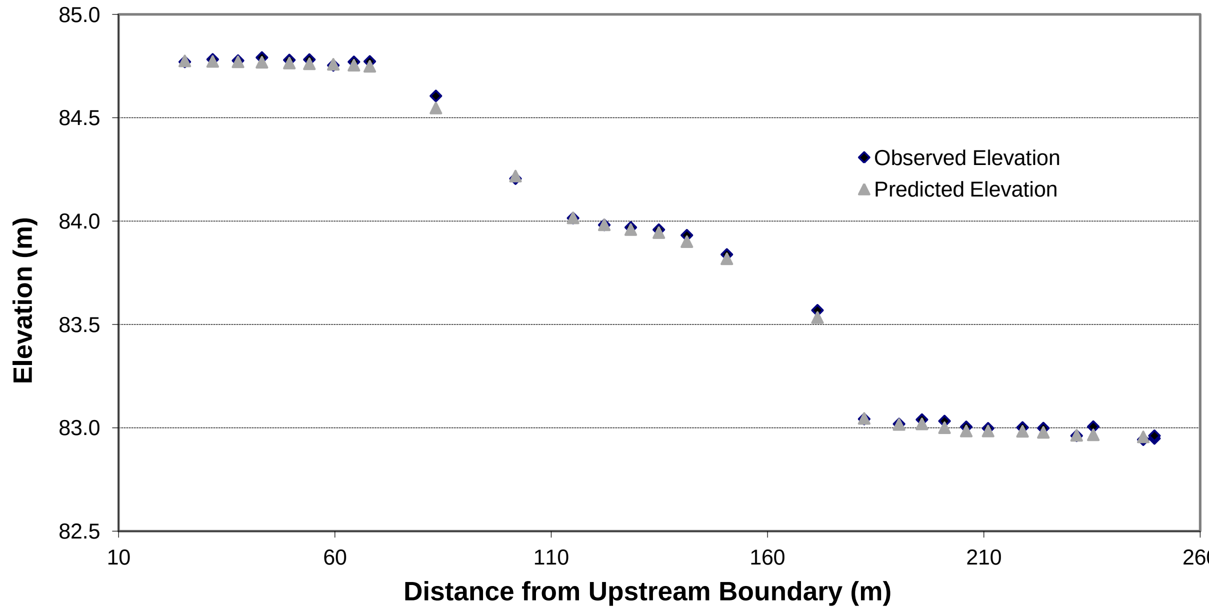

FIGURE 10. Final simulated and observed water surface elevations at 65.7 cfs in the Crandall Creek study site.

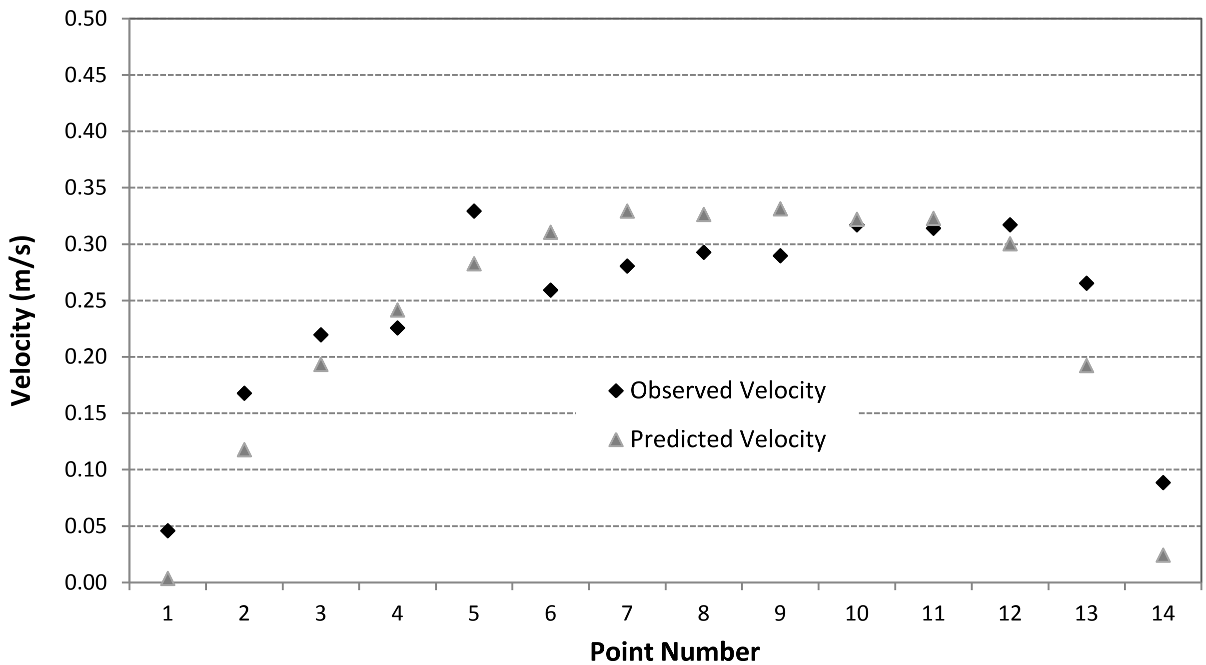

FIGURE 11. Final simulated and observed velocities across a transect at 65.7 cfs in the Crandall Creek study site.

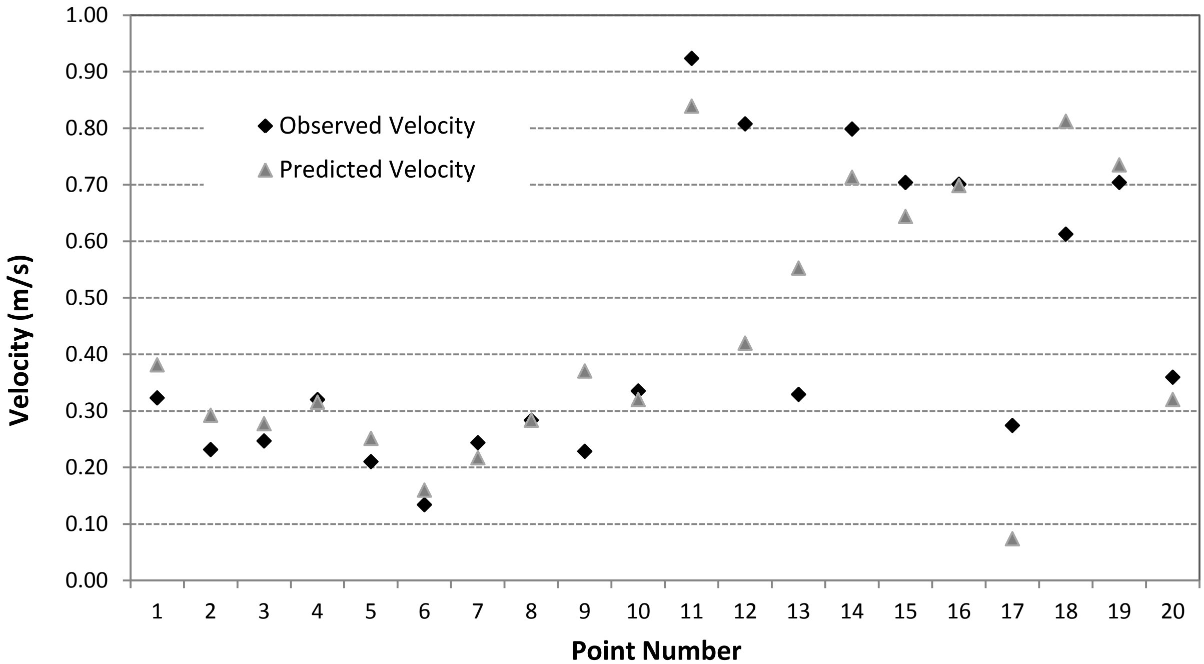

FIGURE 12. Final simulated and observed velocities at 20 randomly selected locations at 65.7 cfs in the Crandall Creek study site.

The model predictions of YCT habitat suitability indicated that for both spawning and juvenile life stages, WUA increases rapidly with increasing flow up to 66 cfs and maintain high WUA through 110 cfs. For the adult life stage, there is a slower increase in WUA up to 100 cfs (Figure 13). There is not a consistent peak habitat condition for all three life stages, but 66 cfs provides the greatest amount of spawning habitat and is the lowest flow in which all three life stages maintain greater than 95% of the peak habitat availability.

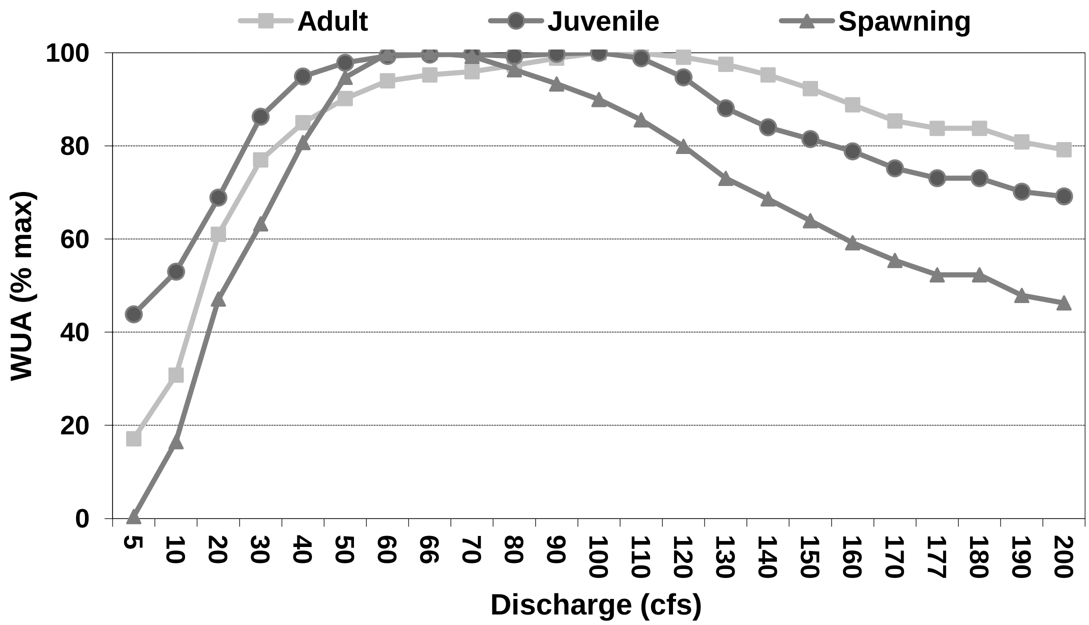

FIGURE 13. Relationship between weighted usable area and discharge for YCT adult, juvenile and spawning life stages in the Crandall Creek study site. X-axis values are not to scale; the values were chosen to highlight important habitat conditions.

Habitat Retention Model

The Habitat Retention Model was used to evaluate hydraulic characteristics that affect the survival and movement of all life stages over a range of discharges in the Crandall Creek instream flow segment (Table 7). Three riffle cross-sections, with an average bankfull discharge of 1240 cfs, were modeled and the resulting discharge needed to maintain the necessary hydraulic criteria was 50 cfs. This flow should maintain base level conditions for fish passage and provide habitat for benthic invertebrate populations on riffles with similar characteristics as the riffle cross-section, though higher flows at some times of year may be needed for other fishery purposes.

TABLE 7. Estimated hydraulic conditions for three riffles over a range of modeled discharges in the Crandall Creek instream flow segment. Bold indicates that the hydraulic criterion was met for an individual attribute; the grayed-out discharge value meets the selection criteria. Because depth is a key criterion the recommendation from Transect 1 entailed meeting all three criteria. Bankfull discharge was estimated to be 1240 cfs.

Riffle Transect Number	Discharge (cfs)	Mean Velocity (ft/sec)	Mean Depth (ft)	Wetted Perimeter (% of bankfull)
1	1240	7.29	2.75	1.00
	50	1.36	**0.75**	0.77
	23	**1.00**	0.50	0.72
	10	0.82	0.30	0.64
	5.0	0.74	0.23	**0.47**
2	1240	6.10	2.31	1.00
	71	2.06	0.77	**0.50**
	50	1.79	**0.73**	0.43
	13	**1.00**	0.42	0.35
	5.0	0.71	0.28	0.28
3	1240	5.95	2.28	1.00
	70	1.74	0.89	**0.50**
	46	1.47	**0.73**	0.47
	12	**1.00**	0.30	0.41
	5.0	0.89	0.25	0.24

Habitat Quality Index Model

The HQI model was used to determine production potential of adult and juvenile YCT in the study site during summer (July through September) flow conditions. The 20% exceedance flow value for September (62 cfs; Table 5) is used as an estimate of existing late summer flow levels for this model. At this flow, the stream provides 119.2 Habitat Units. The instream flow recommendation associated with this model is the lowest streamflow value that provides as many Habitat Units as the 20% exceedance value, which in this case is 55 cfs (Figure 14). The model shows that long-term reductions of late summer flow to levels less than this amount would reduce the productivity of the existing fishery by about 12% or more.

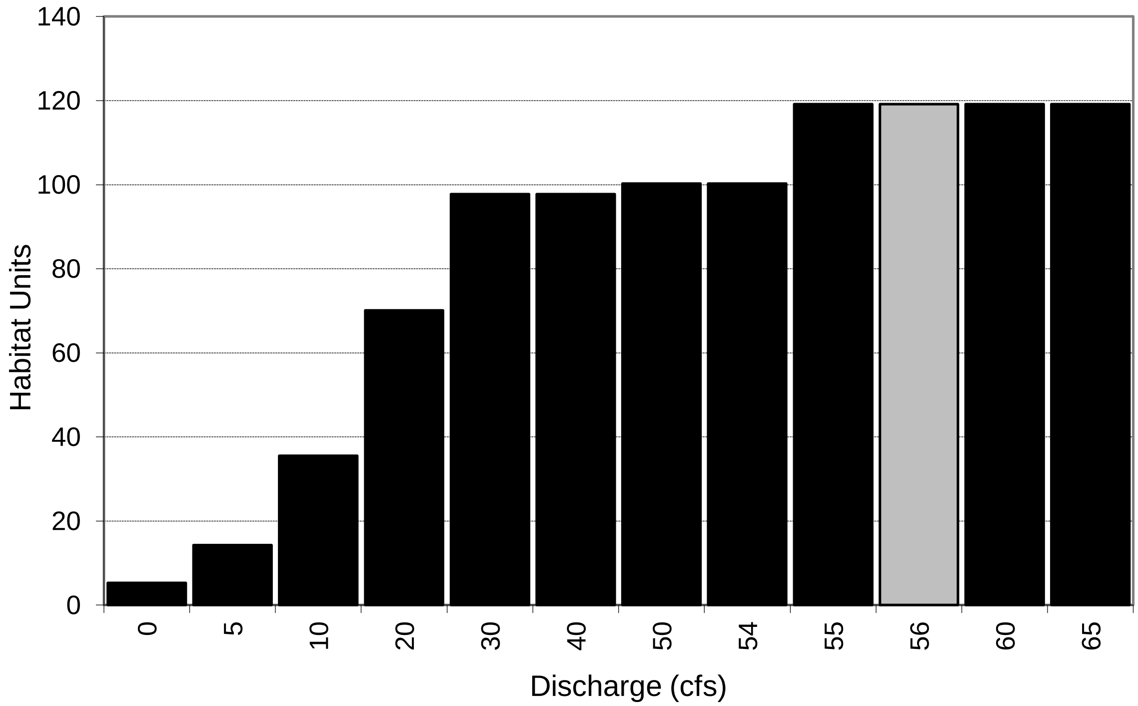

FIGURE 14. Habitat Quality Index vs. discharge in the Crandall Creek instream flow segment. X-axis values are not to scale; the values were chosen to indicate where changes in Habitat Units occur. The recommended flow (55 cfs) is needed to maintain the existing fishery and is indicated by the light shaded bar.

Natural Winter Flow

Between October 1 and April 30, the estimated monthly 20% exceedance values in the proposed instream flow segment ranged from 16 cfs to 45 cfs (Table 5). Natural winter flows of up to 27 cfs, the mean of the 20% monthly exceedance discharges for the winter time period, are needed to maintain over-winter survival of all life stages of YCT at existing levels.

Geomorphology

The proposed instream flow segment in Crandall Creek includes about 40 percent of Rosgen C-type channel with a well developed floodplain, moderate slope (0.8%) and moderate sinuosity (>1.2%). The lower 60 percent of the segment is a Rosgen B-type channel with a steeper slope and lower sinuosity and this extends further downstream to the confluence with the Clarks Fork River. There is some braiding of the main channel in the instream flow segment due to substantial sediment loads and aerial imagery suggests that the channel appears to meander within the floodplain on a regular basis. The wide meandering stream channel results in little riparian shading over the active channel but there is a robust riparian forest adjacent to the floodplain. The portion of the segment that is a B-type channel, and the portion of the stream upstream of the confluence with Hoodoo Creek has more riparian shading. Upstream of the instream flow segment, the stream is a C-type channel in both Crandall Creek and Hoodoo Creek up until the landscape steepens and the streams transition to type B and then to type A streams at the highest elevations.

There was evidence of abundant beaver activity in the riparian forest and a large amount of large woody debris in the stream and on the cobble bar within the study site. Substrates are large throughout the study reach including large cobble, boulders and large sections of exposed bedrock.

A detailed description of recommended channel maintenance flows to sustain the channel form and long-term fisheries habitat processes in the proposed instream flow segment over the long term is presented in Appendix B.

Water Quality

Crandall Creek is a high elevation stream located on National Forest lands and has little development within its catchment. As such, water quality conditions Crandall Creek were assumed to be in very good condition at most times of year and in most years, but could potentially deteriorate with any substantial reduction in flow or alteration of watershed form or function. There is little to suggest water quality impairment now or in the near future.

The NorWeST model generated by the Rocky Mountain Research Station estimates the mean August temperature to be 56.1° F at the downstream end of the Crandall Creek instream flow segment. The NorWeST model also considers future changes in stream temperatures and predicts a mean August temperature of 57.8° F in 2040. Isaak and Hubert (2004) found that cutthroat trout abundance peaked in Wyoming streams around 53.6° F and Carlander (1969) indicates that YCT are commonly found in streams with a temperature range between 40° F and 60° F. Dwyer and Kramer (1975) found that metabolic activity peaks around 59° F. The water temperatures in Crandall Creek appear to favor YCT currently and will continue to be within suitable ranges with even a moderate increase; however, if flow were substantially reduced, water temperatures might increase to a point that YCT would be negatively impacted. Warmer water temperatures (> 60° F) may be more conducive to RBT production than YCT.

A review of the EPA STORET database yielded data from one water quality event on Crandall Creek on September 8, 2009 and one on the tributary stream, Oliver Gulch on August 27, 1997. The Crandall Creek sample was taken downstream of the instream flow segment, close to the confluence with the Clarks Fork River. Oliver Gulch is a small tributary stream that enters Crandall Creek downstream of the instream flow segment. On Crandall Creek, stream discharge was measured as 40.7 cfs during the sample and the water quality conditions of the samples were good. Dissolved oxygen was measured at 7.86 mg/L and water temperature at 57° F. Another common measured variable, pH, was within the WYDEQ (2001) standard range of 6.5-9.0 with a measurement of 8.11. All nutrients, turbidity, conductivity and alkalinity values were low. The only water quality data that were collected at the study site included a single Nitrate + Nitrite – N sample, which was analyzed by the Wyoming Department of Agriculture Analytical Services Laboratory; the result was 0.02 mg/L. On Oliver Gulch, total suspended solids were higher than other samples in the region. Discharge was 5.0 cfs and dissolved oxygen was measured at 8.6 mg/L, water temperature at 57.5° F, and pH at 8.2. All nutrients, turbidity, conductivity and alkalinity values were low. None of the water quality data from these two individual sample point to any concerns for this stream.

The Wyoming Department of Environmental Quality rates Crandall Creek as a "Class 2AB" water (WYDEQ 2013). According to their classification system, "Class 2AB waters are those known to support game fish populations or spawning and nursery areas at least seasonally and all their perennial tributaries and adjacent wetlands and where a game fishery and drinking water use is otherwise attainable. Class 2AB waters include all permanent and seasonal game fisheries and can be either "cold water" or "warm water" depending upon the predominance of cold water or warm water species present. All Class 2AB waters are designated as cold water game fisheries unless identified as a warm water game fishery by a "ww" notation in the Wyoming Surface Water Classification List. Unless it is shown otherwise, these waters are presumed to have sufficient water quality and quantity to support drinking water supplies and are protected for that use. Class 2AB waters are also protected for nongame fisheries, fish consumption, aquatic life other than fish, recreation, wildlife, industry, agriculture and scenic value uses."

Flow recommendations in this report are expected to help maintain water quality within natural bounds and it is assumed that existing water quality features will remain within existing limits of natural variability. If drastic long-term changes to watershed form or function occur, then flow recommendations would need to be reviewed.

Connectivity

There is one road crossing and no diversion structures within the proposed instream flow segment in Crandall Creek, so longitudinal connectivity remains excellent throughout the reach. The one road crossing is a bridge that does not create a barrier to migration. The stream appears to have access to the extensive floodplain throughout the watershed. Stream flow remained very high here throughout the field season which suggests good groundwater contributions, at least in a year with a large snowpack.

Flow recommendations in this report are expected to maintain good connectivity conditions within the instream flow segment. If drastic long-term changes to watershed form or function occur, then flow recommendations would need to be reviewed.

Instream Flow Regime Recommendations

The recommendations for specific seasonal fishery needs for the Crandall Creek instream flow segment are (Table 8; Figure 15):

- Winter (October 1–April 30) – Natural winter flows of up to 27 cfs are needed to maintain over-winter survival of all life stages of YCT at existing levels. This value is the mean of the 20% monthly exceedance discharges for the winter time period (range of 16-45 cfs).
- Spring (May 1 – June 30) – Natural flow up to 66 cfs is needed is needed to maintain sufficient habitat for spawning YCT (River 2D results). This level of flow will maintain existing habitat for this life history need and is consistent with typical flow conditions observed during this period in most years.
- Summer (July 1 – September 30) – Natural flow up to 55 cfs is needed based on HQI results to provide sufficient habitat conditions for growth and production of juvenile and adult YCT.

TABLE 8. Instream flow water right recommendations (cfs) for the proposed instream flow segment in Crandall Creek.

Study Segment	Winter Oct 1 – Apr 30	Spring May 1 – Jun 30*	Summer Jul 1 – Sep 30
Crandall Creek	27	66	55

∗ Channel maintenance flow recommendations for the spring runoff period are defined in Appendix B.

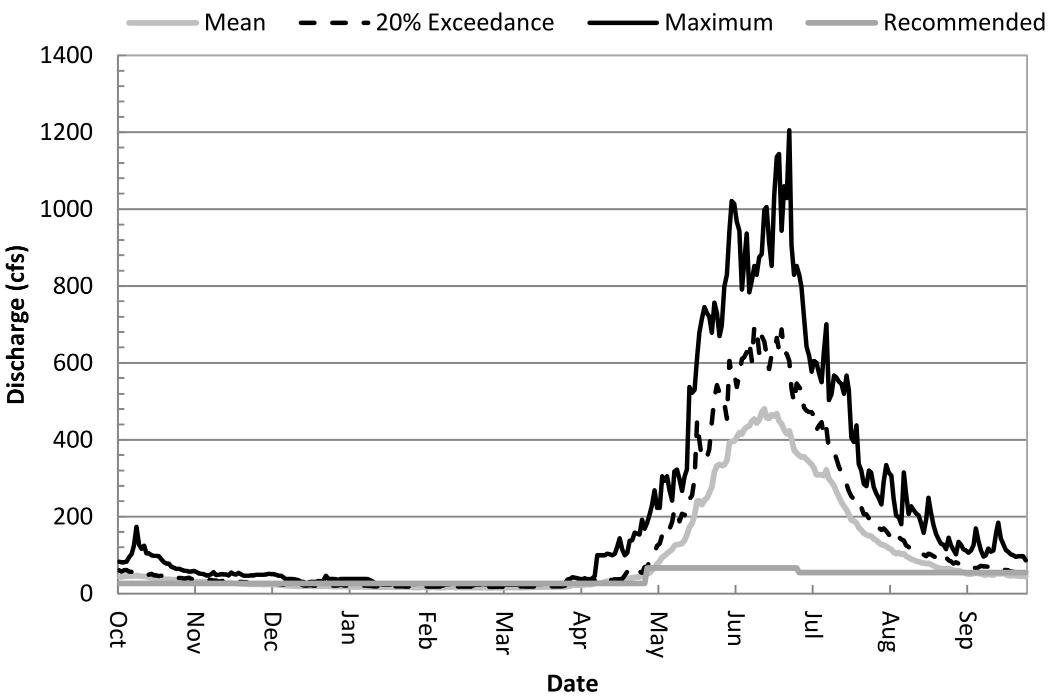

FIGURE 15. Recommended instream flow water right in the proposed segment relative to mean, 20 percent exceedance, and maximum daily discharge estimates.

DISCUSSION

Crandall Creek provides important YCT habitat to one of the few remaining conservation populations in the Clarks Fork River drainage. Protecting stream flows that provide this habitat and support the population of trout will help ensure the long-term persistence of the species in the Absaroka Mountains and throughout Wyoming. This action will also support the state's interests by adding to conservation actions needed to keep the species from being listed as threatened or endangered by the federal government. This population is managed as a wild YCT fishery within the Shoshone National Forest. If approved by the State Engineer, the proposed instream flow water right filing on Crandall Creek will maintain existing base flow conditions, when naturally available, against potential future out-of-channel uses up to the permitted amount. Approximately 1.7 miles of stream habitat will be directly maintained in Crandall Creek. If drastic long-term changes to watershed form or function occur, then flow recommendations would need to be reviewed.

ACKNOWLEDGEMENTS

Data was collected with the help of Wyoming Game and Fish Department fisheries technician Anthony Winn Input on various aspects of the study was received from the Cody Region fish management crew. Tom Annear reviewed the manuscript and provided constructive comments that greatly improved the quality and clarity of the report.

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APPENDIX A. INSTREAM FLOWS IN WYOMING

Legal and Institutional Background

The instream flow law, W.S. 41-3-1001-1014, was passed in 1986 and establishes that "unappropriated water flowing in any stream or drainage in Wyoming may be appropriated for instream flows to maintain or improve existing fisheries and declared a beneficial use..." The statute directs that the Wyoming Game and Fish Commission (WGFC) is responsible for determining stream flows that will "maintain or improve" important fisheries. The Wyoming Game and Fish Department (WGFD) fulfills this function under the general policy oversight of the WGFC. The WGFD conducts biological studies to determine the quantity of flow needed to maintain or improve fisheries. The Wyoming Water Development Office conducts a feasibility study to determine the availability of flow to meet the recommendations and submits the instream flow water right applications. If approved by the State Engineer, instream flow water rights are held by the state and administered by the Wyoming Water Development Office. The priority date for the instream flow water right is the day the application is received by the State Engineer. As with all other water rights in Wyoming, the doctrine of prior appropriation applies and instream flow water rights are junior to all existing water rights in the stream. Permitted instream flow water rights will not affect the lawful use of water for senior rights up to the limits of those rights.

Biological Studies

Studies designed to evaluate instream flow needs for fisheries in Wyoming are initiated by the WGFC. Important stream fisheries are identified throughout the state and studies are conducted in each stream to determine how much flow is needed to maintain or improve these fisheries. A comprehensive instream flow study is designed to consider all five riverine ecosystem components (hydrology, biology, geomorphology, water quality and connectivity) and all aspects of each component (e.g., long-term habitat processes; Annear et al. 2004); however, the instream flow statute has been interpreted by the Wyoming State Engineer's Office as applying only to direct fishery response to short-term changes in low or base flow. Other important components that influence stream conditions and fish populations, such as geomorphology, water quality and connectivity, are not considered when making instream flow recommendations (though information is provided in the study reports, where available).

From a natural resource perspective, a fishery includes the habitat and associated natural processes that are required to support fish populations. The primary components that comprise physical habitat include, but are not limited to, the stream channel, riparian zone and floodplain as well as the processes of sediment flux and riparian vegetation development that sustain those habitats (Annear et al. 2004). To maintain the existing dynamic character of an entire fishery, instream flow regimes must maintain the stream channel and its functional linkages to the riparian corridor and floodplain to perpetuate habitat structure and ecological function. Until the interpretation of state water law changes to include a full range of flows of a dynamic fishery, channel maintenance flow recommendations are not included on instream flow applications leaving the existing fishery at risk of degradation if those higher flows are depleted. Channel maintenance recommendations are presented in an appendix of the biological studies report.

Guiding Principles for Instream Flow Recommendations

The analyses and interpretation of data collected for instream flow studies include consideration of the important components of an aquatic ecosystem and their relationship to stream flow. Stream ecosystems are complex, and maintaining this complexity requires an appropriate flow regime. The recommendations of the Instream Flow Council (IFC), an organization of state and provincial fishery and wildlife management agencies, provide comprehensive guidance on conducting instream flow studies. The approach described by the IFC includes consideration of three policy components (legal, institutional, and public involvement) and five riverine components (hydrology, geomorphology, biology, water quality and connectivity; Annear et al. 2004). By using the eight components described by the IFC as a guide, WGFD strives to develop instream flow recommendations that work within Wyoming's legal and institutional environment to maintain or improve important aquatic resources for public benefit while also employing a generally recognized flow quantification protocol.

Public Participation

The general public has several opportunities to be involved in the process of identifying instream flow segments or commenting on instream flow applications. Individuals or groups can inform WGFD of their interest in protecting the fisheries at any time in specific streams or stream segments with instream flow filings. In addition, planning and selection of future instream flow study sites are detailed in the WGFD Water Management Unit's work plan (Robertson and Annear 2011).

The public is also able to comment on instream flow water rights that have been filed with the State Engineer through public hearings, which are required by statute and conducted by the State Engineer's Office for each proposed instream flow water right. The State Engineer uses these public hearings to gather information for consideration related to injury of existing water rights before issuing a decision on the instream flow water right application.

Instream flow segments are nearly always located on public land; however, landowners adjacent to a proposed segment have the opportunity to request that the state extend an instream flow segment on the portion or portions of those streams crossing their property. Any such requests must be made in writing to the department. Instream flow segments are not located on private lands without such a request.

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APPENDIX B. CHANNEL MAINTENANCE FLOWS

Background

Maintaining a dynamic flow regime within the natural range of variability and including occasional high flows, is important in streams for maintaining diverse in-channel habitat for fisheries and riparian and floodplain vegetation (Kuhnle et al. 1999). A managed flow regime should mimic natural dynamic hydrographs within and between years (Gordon 1995, Trush and McBain 2000, Schmidt and Potyondy 2004) and include these higher flows that maintain the channel form and habitat conditions for fish over the long term (decades). High flows are needed in some years to scour the stream channel, prevent encroachment of stream banks, and deposit sediments on the floodplain to maintain a dynamic alternate bar morphology and a riparian community with diverse successional states (Carling 1995, Annear et al. 2004, Locke et al. 2008). Low flow years allow establishment of riparian seedlings on bars deposited in immediately preceding wet years (Trush and McBain 2000). Any time water is extracted from a stream the natural dynamic patterns change; larger quantities of extraction have a greater impact on habitat conditions and the organisms associated with those habitats. If naturally-occurring high flows were substantially reduced on a regular basis, it would have negative impacts on habitat, riparian assemblage of plants and animals, and ultimately the resident fishery (Stromberg and Patten 1990, Rood et al. 1995, Mahoney and Rood 1998).

The term “channel maintenance flows” refers to flows that maintain existing channel morphology, riparian vegetation and floodplain function (Schmidt and Potyondy 2004). The basis and approach used for defining channel maintenance flows applies to snowmelt-dominated gravel and cobble-bed (alluvial) streams and “identifies the minimum essential regime of streamflows necessary for the channel and its floodplain to remain fully functioning with respect to sediment and flow conveyance.” These are streams whose beds are dominated by loose material with median sizes larger than 0.08 in. and with a pavement or armor layer of coarser materials overlaying the channel bed. In these streams, bedload transport processes determine the size and shape of the channel and the character of habitat for aquatic organisms (Andrews 1984, Hill et al. 1991, Leopold 1994).

A flow regime that includes sufficient flow for channel maintenance results in stream channels that are in approximate sediment equilibrium, where sediment export equals sediment import on average over a period of years (Leopold 1994, Carling 1995, Schmidt and Potyondy 2004). Thus, stream channel characteristics over space and time are a function of sediment input and flow (Schmidt and Potyondy 2004). When sediment-moving flows are removed or reduced over a period of years, some gravel-bed channels respond with reductions in width and depth, rate of lateral migration, stream-bed elevation, stream side vegetation, water-carrying capacity, and changes in bed material composition.

Channel maintenance flows must be sufficient to move the entire volume and all sizes of material supplied to the channel from the watershed over a long-term period (Carling 1995, Schmidt and Potyondy 2004). A range of flows, under the dynamic hydrograph paradigm, provides this function. Infrequent high flows move large bed elements while the majority of the total volume of material is moved by more frequent but lower flows (Wolman and Miller 1960, Leopold 1994). In streams with a wide range of sediment sizes on the channel boundary, a range of flows may best represent the dominant discharge because different flow velocities are needed to mobilize different sizes of bed load and sediment. Kuhnle et al. (1999) noted “A system designed with one steady flow to transport the supplied mass of sediment would in all likelihood become unstable as the channel aggraded and could no longer convey the sediment and water supplied to it."

Bedload Transport

A bedload transport model (Figure B-1) shows the total amount of bedload sediment transported over time (during which a full range of stream discharge [Q] values occur). Smaller discharges, such as the substrate mobilization flow (Q_m) occur more frequently, but not much sediment is moved during those times. The effective discharge (Q_e) mobilizes the greatest volume of sediment and also begins to transport some of the larger sediment particles (gravels and small cobbles). The bankfull discharge (Q_{bf}), in which flow begins to inundate the floodplain and which has a return interval of approximately 1.5 years on average, typically occurs near the Q_e. The discharge corresponding to the 25-year return interval (Q_{25}) represents the upper limit of the required channel maintenance flow regime, since the full range of mobile sediment materials move at flows up to this value, but these higher flows are infrequent. The more frequent discharges that occur between the Q_m and the Q_e move primarily smaller-sized particles (sand and small gravel) and prevent filling in of pools and other reduction in habitat complexity. Since these particles are deposited into the stream from the surrounding watershed with greater frequency, it is important to maintain a flow regime that provides sufficient conveyance properties (high frequency of moderate discharges) to move these particles through the system. However, alluvial streams, particularly those at higher elevations, also receive significant contributions of larger-sized particles from the surrounding watershed and restrictions to the flow regime that prevent or reduce the occurrence of flows greater than Q_e (which are critical for moving these coarser materials) would result in gradual bedload accumulation of these larger particles. The net effect would be an alteration of existing channel forming processes and habitat (Bohn and King 2001). For this reason, flows up to the Q_{25} flow are required to maintain existing channel form and critical habitat features for local fish populations.

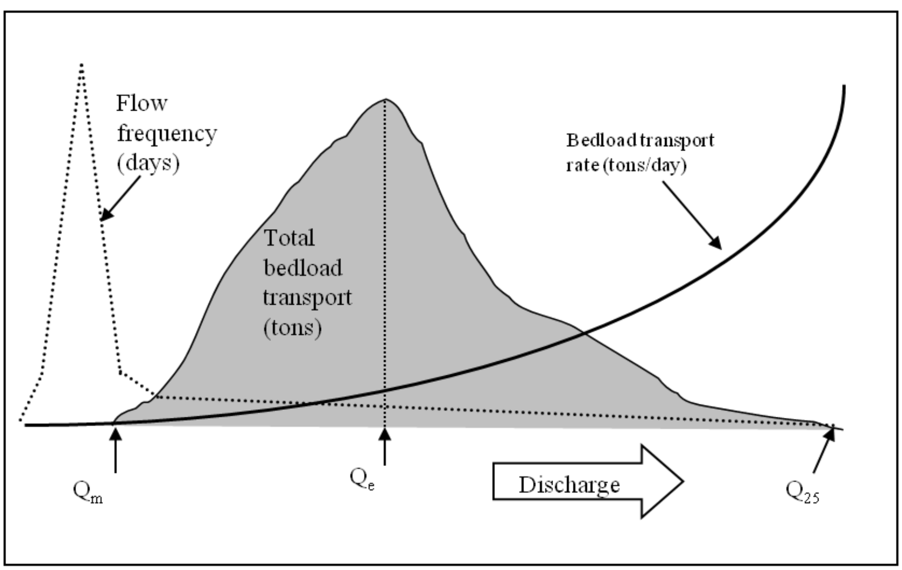

FIGURE B-1. Total bedload transport as a function of bedload transport rate and flow frequency (adapted from Schmidt and Potyondy 2004).

Channel Maintenance Flows Model

The model used to recommend flows to maintain the form and function of the stream channel is derived from bedload transport theory presented above. Based on these principles, the following channel maintenance flow model was developed by Dr. Luna Leopold and is used in this report to calculate the appropriate instream flows up to the Q_{25}:

$$Q\ \text{Recommendation} = Q_f + \{(Q_s - Q_f) * [(Q_s - Q_m) / (Q_{bf} - Q_m)]^{0.1}\}$$

Where: Q_s = actual stream flow
Q_f = fish flow (required to maintain fish spawning habitat)
Q_m= sediment mobilization flow = 0.8 * Q_{bf}
Q_{bf} = bankfull flow

The Leopold model calculations could be used to yield a continuous range of instream flow recommendations at flows between the Q_m and Q_{bf} for each cubic foot per second increase in discharge. However, this manner of flow regulation is complex and could prove burdensome to water managers. To facilitate flow administration while still ensuring sufficient flows for channel maintenance, we modified this aspect of the approach to recommend a single instream flow for each of four quartiles between the Q_m and Q_{bf}.

Channel maintenance flow recommendations developed with the Leopold model require that only a portion of the flow remain instream for maintenance efforts. When total discharge is less than Q_m, only fish flows are necessary; discharge between the fish habitat flows recommended in the main body of this report and Q_m is available for other uses (Figure B-2). Similarly, all discharge greater than the Q_{25} flow is less critical for channel maintenance purposes and available for other uses (these higher flows do allow a connection to the floodplain and it is valuable for infrequent inundation of riparian habitat to occur, but not for the physical maintenance of the stream channel). Between the Q_m and Q_{bf}, the model is used to determine what proportion of flow should remain in channel for maintenance activities. For those relatively infrequent flows that occur in the range between Q_{bf} and the Q_{25}, all flow is recommended to remain in the channel for these critical channel maintenance purposes.

Using this “dynamic hydrograph” approach, the volume of water required for channel maintenance is variable from year to year. During low-flow years, less water is recommended for channel maintenance because flows may not reach the defined channel maintenance level. In those years, most water in excess of fish habitat flows is available for other uses. The majority of flow for channel maintenance occurs during wet years. One benefit of this dynamic hydrograph approach is that the recommended flow is needed only when it is available in the channel and does not assert a claim for water that is not there as often happens with a threshold approach.

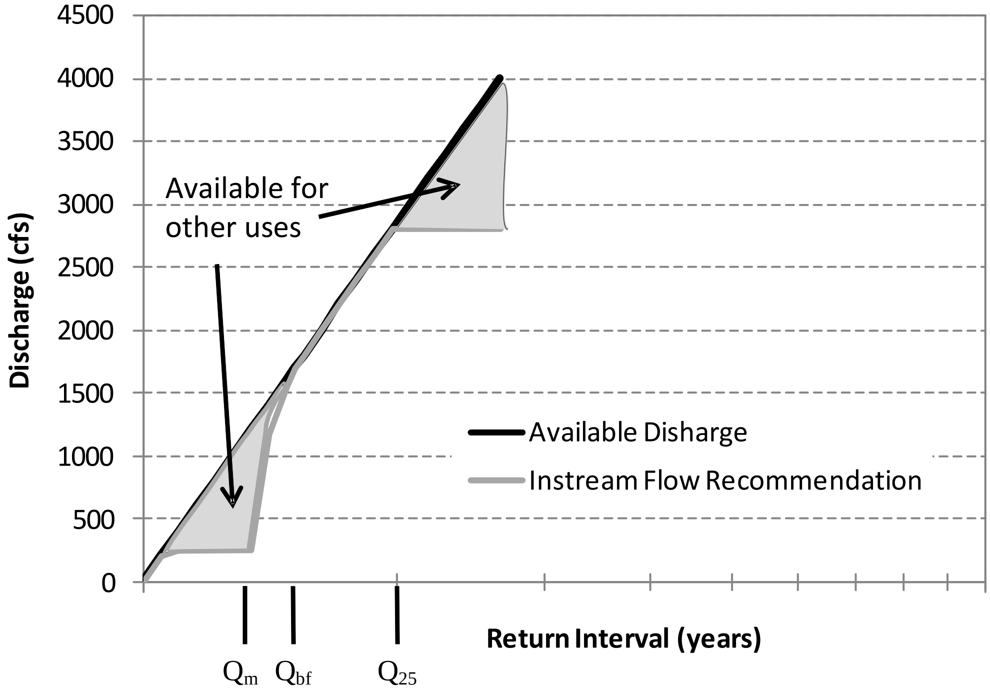

FIGURE B-2. Generalized dynamic hydrograph indicating recommended instream flow for fishery maintenance. Q_m is substrate mobilization flow, Q_{bf} is bankfull flow, and Q_{25} is the discharge with a 25-year return interval.

This channel maintenance flow model is the same as the one presented in Gordon (1995) and the Clark's Fork instream flow water right (C112.0F) filed by the U.S. Forest Service with the Wyoming State Engineer, with one exception. The model presented in those documents used the average annual flow to represent Q_m. Subsequent work by Schmidt and Potyondy (2004) identified Q_m as occurring at a discharge of 0.8 times Q_{bf}. Initial particle transport begins at flows somewhat greater than average annual flows but lower than Q_{bf} (Schmidt and Potyondy 2004). Ryan (1996) and Emmett (1975) found the flows that generally initiated transport were between 0.3 and 0.5 of Q_{bf}. Movement of coarser particles begins at flows of about 0.5 to 0.8 of Q_{bf} (Leopold 1994, Carling 1995). Schmidt and Potyondy (2004) discuss phases of bedload movement and suggest that a flow trigger of 0.8 of the Q_{bf} "provides a good first approximation for general application" in defining flows needed to maintain channels.

Crandall Creek

Like all properly functioning rivers, Crandall Creek has a hydraulically connected watershed, floodplain, riparian zone, and stream channel. Bankfull and overbank flow are essential hydrologic characteristics for maintaining the habitat in and along these river segments in their existing dynamic form. These high flows flush sediments from the gravels and maintain channel form (i.e., depth, width, and pool and riffle configuration) by periodically scouring encroaching vegetation. Overbank flow maintains recruitment of riparian vegetation, encourages lateral movement of the channel, and recharges ground water tables. Instream flows that maintain the connectivity of these processes over time and space are needed to maintain the existing fishery (Annear et al. 2004).

The Leopold model was used to develop channel maintenance recommendations for the Crandall Creek instream flow segment (Table B-1). The fish flow used in the analysis was the spring spawning flow (66 cfs). For naturally available flow levels less than the spawning flow, the channel maintenance instream flow recommendation is equal to natural flow. The spawning flow level is substantially less than Q_m (620 cfs). For the flow range between the spawning flow and Q_m, the channel maintenance flow recommendation is equal to the spawning flow (Table B-1). When naturally available flows range from Q_m to Q_{bf} (775 cfs), the Leopold formula is applied and results in incrementally greater amounts of water applied toward instream flow (Table B-1). At flows between Q_{bf}, and Q_{25} (1852 cfs), all stream flow is retained in the channel to perform maintenance functions. At flows greater than Q_{25}, only the Q_{25} flow is recommended for channel maintenance (Figure B-3).

TABLE B-1. Channel maintenance instream flow recommendations (May 1–Jun 30) to maintain existing channel forming processes and long-term aquatic habitat characteristics in the Crandall Creek instream flow segment.

Flow Description	**Available Flow (cfs)**	**Recommended Flow (cfs)**
<Spawning Flow	<66	All available flow
Spawning Flow to Q_m	66-620	66
Q_m to Q_{bf} – Quartile 1	621-659	401
Q_m to Q_{bf} – Quartile 2	660-698	584
Q_m to Q_{bf} – Quartile 3	699-736	657
Q_m to Q_{bf} – Quartile 4	737-775	719
Q_{bf} to Q_{25}	775-1852	All available flow
> Q_{25}	≥ 1852	1852

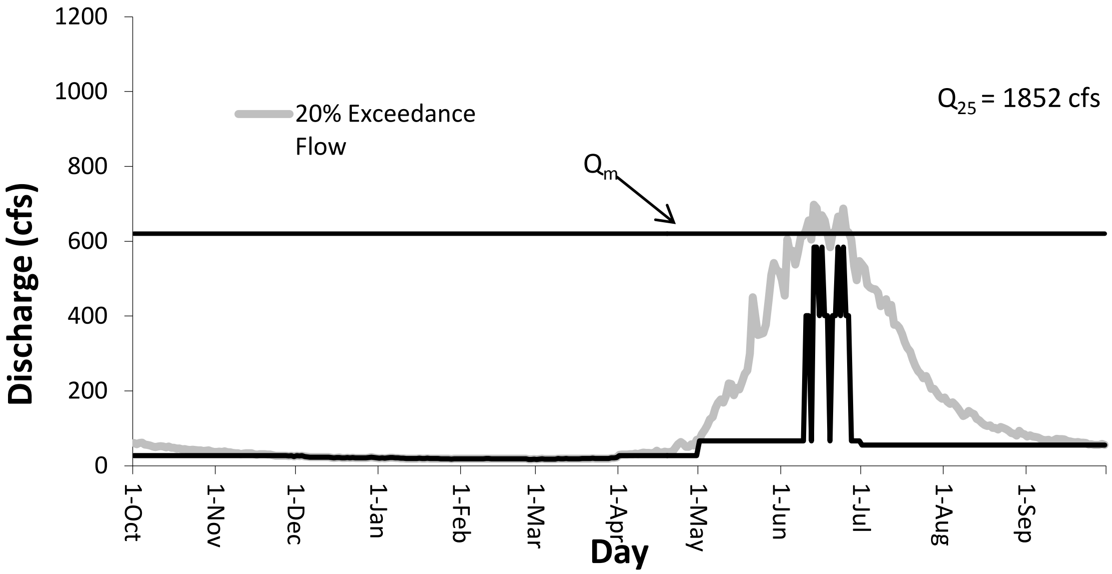

FIGURE B-3. Channel maintenance flow recommendations and hydrograph for the Crandall Creek instream flow segment if the flow were at the 20% exceedance flow all year.

Implementing these flow recommendations would have to include moderating the abrupt changes that occur at threshold flows with a ramping scheme that includes more gradual changes akin to a natural hydrograph. Such sharp flow increases and decreases evident in Figure B-3 would cause habitat loss through excessive scour and potential trout mortality due to stranding. In addition, spawning redds may be disturbed and fish recruitment negatively impacted without an appropriate ramping rate. The Index of Hydrologic Alteration (IHA; Richter et al. 1996) or other hydrologic summary models could provide a valuable reference to find suitable rates of change. Daily increases and decreases during runoff measured at the reference gage could serve as a guide for developing such ramping rate recommendations using the IHA.

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APPENDIX C. HYDROLOGY ESTIMATES FOR THE UNGAGED STUDY SEGMENT

There are multiple methods for generating daily discharge estimates in ungaged stream segments, but the one chosen for these estimates is based on watershed characteristics that can primarily be calculated from maps and climatology data from the study area. The data are supported by field observations, but the estimates are not based on measurements of flow in the study reach. These results do provide flow estimates with strong supporting documentation (e.g., the underlying formulas are based on extensive field investigations), but these results could be paired with a local study using extensive field data (e.g., Lowham 2009) to generate comprehensive flow estimates that have a higher probability of accuracy than either method used alone. An excellent example of how multiple flow estimation methods can be combined into a single set of daily discharge estimates is described in Parrett and Cartier (1990).

Reference gage selection

To estimate flows in an ungaged stream using a watershed characteristics model, a reference stream gage is first selected to provide baseline discharge data. The qualities of a good reference gage are: 1) that it be located close to the study site; within the same eight-digit HUC drainage is preferred, where possible, 2) that it have at least 10 years of continuous records; it is not necessary that it be in current operation, but this is preferable, and 3) that be in a stream with similar watershed characteristics (mean elevation, drainage area, stream width, etc.). Due to the limited number of stream gages in Wyoming, this combination is difficult to find for many study sites. Once a reference gage is selected, the recorded flow estimates from that gage are adjusted to correct for differences between it and the ungaged study stream. After this correction factor is applied, the period of record at the reference gage can be used to estimate flows over the same period, including generating monthly and annual summary statistics, at the study site.

In the area near the Crandall Creek study site, there are 2 active and 2 inactive USGS stream gaging sites that have more than 20 years of data and were considered as potential reference gages (Table C-1). One active USGS gage with 16 years for a period of record was also considered. There were no local stream gages found on the Wyoming State Engineer's website for real-time stream flow data (http://seoflow.wyo.gov/WDPortal/). All USGS gages were within the same HUC6 watershed (100700). The active gage on the Lamar River and the inactive gage on the Clarks Fork River both drain large basins (660 and 446 sq. miles, respectively), both larger than the 111 square mile drainage area of the Crandall Creek instream flow segment. The active gage in Rock Creek and the inactive gage in Sunlight Creek both have smaller drainage basins of 105 and 135 square miles, respectively, making these better candidates. The Soda Butte Creek gage had a drainage area size of 31 square miles. The Sunlight Creek gage was closer to the Crandall Creek study site than all of the others and was also located at a similar elevation to the study site. Based on these observations, the reference gage chosen to estimate conditions at the Crandall Creek study site was the one on Sunlight Creek (06206500).

TABLE C-1. Potential USGS reference gages.

Gage Name	Gage Number	Period of Record	Drainage Area	Elevation (ft)
Lamar River near Tower Ranger Station YNP	06188000	1923-2015	660	6,000
Rock Creek near Red Lodge MT	06209500	1932-2015	105	6,400
Clarks Fork River below Crandall Creek	06206000	1929-1957	446	6,160
Sunlight Creek near Painter, WY	06206500	1945-1971	135	6,700
Soda Butte Cr at Park Boundary at Silver Gate	06187915	1998-2015	31	7,340

Watershed Model Selection

After selecting a reference gage, models using various watershed characteristics were evaluated to determine which watershed model is best suited to the conditions in the study area. There are several potential models that use variables that include mean elevation, drainage area, precipitation, stream length, and bankfull width to estimate mean annual flow (Q_{AA}). In Wyoming streams, models for making these estimates are found in two primary sources, Lowham (1988) and Miselis et al. (1999). The Lowham (1988) models were based on streams found in mountainous areas statewide and the Miselis et al. (1999) models created separate models for each of eight specific mountain ranges. Each model is used to estimate Q_{AA} at the reference gage and the result is compared to the known Q_{AA} value. The watershed characteristics model that best predicts Q_{AA} at the reference gage is a good prospect for predicting Q_{AA} at the ungaged study site, though sometimes a detailed evaluation may provide support for an alternate model. Local discharge measurements or temporary stream gaging data at the study site provide additional data sources, when available, to help guide model selection.

The Q_{AA} for the Sunlight Creek reference gage (06206500) was 128 cfs for the 26 year period of record (1945-1971). Table C-2 shows how closely each of several possible models comes to estimating the actual Q_{AA} for this location. The model that best predicts discharge at the reference gage is the Miselis (1999) model that uses drainage area as the primary variable and it was chosen for estimating flows at the ungaged study site.

TABLE C-2. Watershed models used to calculate Q_{AA} for the Sunlight Creek reference gage.

Model Description	**Model***	**Upper Shell Q_{AA} (cfs)**
Miselis et al (1999): Mountainous for WY, Drainage Area	$1.20976\ DA^{0.894}$	97
Miselis et al (1999): Absaroka Mountains, Mean Elevation	$4.47e40\ BE^{-9.74}$	232
Miselis et al (1999): Absaroka Mountains, Drainage Area	$0.43441\ DA^{1.15}$	122
Miselis et al (1999): Absaroka Mountains, Precipitation	$0.00014\ P^{4.50}$	50
Miselis et al (1999): Absaroka Mountains, Stream Length	$0.48040\ SL^{1.80}$	152
Miselis et al (1999): Absaroka Mountains, Bankfull Width	$0.01626\ WBF^{2.14}$	178
Lowham (1988): Drainage area and Mean Elevation	$0.0015DA^{1.01}(Elev/1000)^{2.88}$	102
Lowham (1988): Drainage area and Precipitation	$0.013DA^{0.93}P^{1.43}$	72
Lowham (1988): Bankfull Width	$0.087\ W_{BF}^{1.79}$	208
Historic gage records (26 years of record)		**128**

*-Basin characteristics include: DA – drainage area (square miles); P – annual precipitation (inches); SL – stream length (miles); Elev – mean basin elevation (feet); Wbf – Bankfull channel width (feet).

Dimensionless analysis

Once the watershed characteristics model was selected, a dimensionless analysis approach was used to develop estimates of daily flow, annual and monthly flow duration curves, and flood frequency for the proposed instream flow segment. The procedure uses the difference in the scale of the known Q_{AA} at the reference gage and the estimated Q_{AA} at the ungaged study sites to shift data from the reference gage up or down by the appropriate correction factor to estimates for the ungaged study site. The adjustment factor is a dimensionless value that uses average annual discharge (Q_{AA}) for scaling according to the formula:

$$\frac{Q_1}{Q_{AA1}} = \frac{Q_2}{Q_{AA2}}$$

Where:
Q_1 = Daily discharge at the gage location
Q_{AA1} = Average annual discharge at the gage location
Q_2 = Daily discharge at the ungaged study segment
Q_{AA2} = Average annual discharge at the ungaged study segment

Daily discharge and Q_{AA} are known at the gage location. The watershed model provides the Q_{AA} estimate at the ungaged study site so the formula is rearranged to solve for Q_2 (daily discharge at the ungaged location).

Flow Estimates for the Crandall Creek Study Site

Using the watershed characteristics model of Miselis (1999) based on drainage area ($0.43441*DA^{1.15}$), Q_{AA} at the Crandall Creek study site was estimated to be 98 cfs. Daily flows were estimated for the study site over the same period of record as the reference gage (1945-

1971) and a graph of mean, 20 percent exceedance, and maximum daily discharge was prepared (Figure C-1). A flood frequency series (Table C-3) was calculated using the Log-Pearson Type III method and annual (Table C-4) and monthly (Table C-5) flow duration series were also calculated.

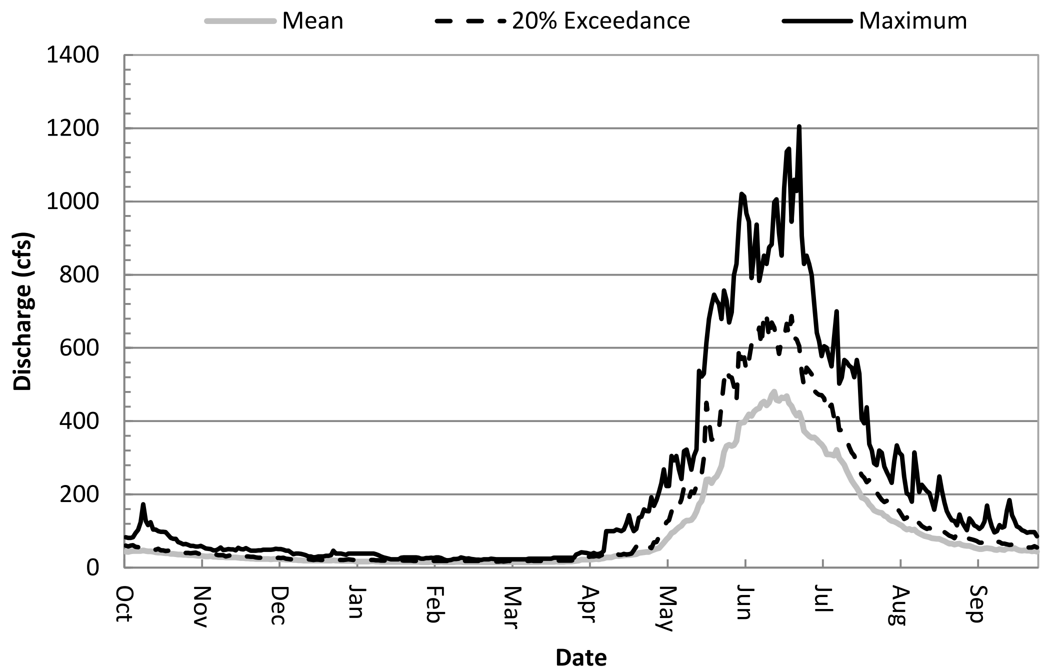

FIGURE C-1. Hydrograph showing the mean, 20 percent exceedance, and maximum daily discharge estimates for the for the Crandall Creek study site.

Table C-3. Annual flow duration curve data for the Sunlight Creek reference gage and estimated values at the Crandall Creek study site.

Return Period (years)	Sunlight Creek (1945-1971)	Dimensionless (Q/QAA using gage data)	Crandall Creek
1.01	860	6.741	660
1.05	877	6.876	674
1.11	900	7.054	691
1.25	945	7.404	725
1.5	1010	7.913	775
2	1112	8.717	854
5	1481	11.606	1137
10	1828	14.325	1403
25	2413	18.906	1852

Table C-4. Annual flow duration curve data for the Sunlight Creek reference gage and estimated values at the Crandall Creek study site.

Duration Class (% Time Flow Equaled or Exceeded)	Annual Flow Sunlight Creek (1945-1971)	Dimensionless (Q/QAA using gage data)	Predicted Annual Flow Crandall Creek
95	16	0.125	12
90	18	0.141	14
85	20	0.153	15
80	21	0.165	16
75	23	0.180	18
70	25	0.196	19
65	28	0.215	21
60	30	0.235	23
55	35	0.274	27
50	40	0.313	31
45	48	0.376	37
40	56	0.439	43
35	75	0.584	57
30	93	0.729	71
25	140	1.093	107
20	186	1.457	143
15	286	2.237	219
10	385	3.017	296
5	560	4.388	430

Table C-5. Monthly flow duration curve estimates for the Crandall Creek study site.

Duration Class (% time flow equaled or exceeded)	Streamflow (cfs)											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
95	21	18	12	12	11	11	14	24	177	100	45	25
90	24	18	15	12	12	12	15	32	201	121	48	29
85	25	19	15	12	12	12	15	44	227	136	52	31
80	27	21	15	12	12	13	16	52	250	151	56	32
75	28	21	16	12	12	13	17	62	273	164	60	34
70	29	22	16	14	12	14	18	76	297	175	64	36
65	30	23	18	15	14	14	19	88	320	189	68	38
60	31	23	18	15	14	15	20	104	342	203	71	40
55	33	24	18	15	14	15	21	117	361	215	75	41
50	34	25	19	15	15	15	23	131	380	230	81	44
45	36	25	19	15	15	15	27	146	407	244	86	46
40	38	26	19	16	15	15	28	159	431	264	91	48
35	39	27	20	17	15	15	31	177	464	286	96	51
30	41	28	21	18	15	16	32	197	501	310	100	54
25	43	30	21	18	16	16	35	222	537	331	107	58
20	45	31	23	18	16	18	36	253	595	361	115	62
15	50	32	23	19	17	18	42	305	633	390	128	70
10	58	34	25	21	18	19	54	399	691	445	144	77
5	77	41	31	23	20	20	100	528	761	511	167	92

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